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This Master's Project

**Carbon biogeochemical cycling in the Sierra Nevada:
How to maintain the Sierra Nevada as a net carbon sink over the long-term**

by

Eric Canteenwala

is submitted in partial fulfillment of the requirements

for the degree of:

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List of Acronyms and Abbreviations

Cal Fire	California Department of Forestry and Fire Protection
CEQA	California Environmental Quality Act
EIS	Environmental Impact Statement
FIA	US Forest Service Forest Inventory Analysis Program
ghg	Greenhouse gas
Landfire	United States Geological Survey's Landscape Fire and Resource Management Planning Tool
MMT CO ₂ e	Million Metric tons of Carbon dioxide equivalent
NCEB	Net Carbon Ecosystem Balance
NEPA	National Environmental Policy Act of 1969
U.S. EPA	United States Environmental Protection Agency
USFS	United States Forest Service
WUI	Wildland Urban Interface

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Abstract

The Sierra Nevada region is an important carbon sink, storing about 3500 MMTCO₂e or eight times the total amount of carbon emitted annually throughout California. However, recent climate-driven disturbances such as wildfires, drought and bark beetle infestations threaten the stability of this carbon pool over the long-term. The existing literature on how treatments impact carbon biogeochemical cycling in the Sierra Nevada was reviewed and interviews were used to identify the top barriers to increasing the pace and scale of treatments. Combinations of forest management treatments such as thinning, prescribed fire and reforestation can help maintain the Sierra Nevada as a net carbon sink over the long-term by altering forest stand density, species composition and fire regimes. These forest attributes increase resilience to mortality from severe wildfires, drought and, insects and bolster the long-term stability of carbon pools in the Sierra Nevada. Despite a consensus on the urgent need for increasing treatments, a significant gap exists between the number of acres that need treatment (over 15 million statewide) and total number of acres treated annually (around 275,000). Funding, permitting and regulatory requirements, and low implementation capacity are the greatest impediments to increased forest treatments. To meet overall forest resiliency goals, around 300,000 acres per year would need to be treated in the Sierra Nevada, conservatively costing \$300 million annually. In comparison, the co-benefits of treatments including protection of life and property, improved air quality, water availability and quality, jobs and, economic opportunity for underserved communities was valued at \$61.551 billion in 2018. A federal Civilian Climate Corps, streamlined permitting, and development of new markets for treatment byproducts can help increase the pace and scale of treatments to ensure the long-term stability of Sierra Nevada carbon stocks and meet California's ambitious greenhouse gas reduction goals.

I. Introduction

Currently, the Sierra Nevada region stores a significant amount of carbon above ground in live and dead trees, live and dead understory vegetation, down wood and vegetative litter and below ground in roots and soil organic carbon. Each of these storage areas are referred to as carbon pools. The major carbon pools in the Sierra Nevada are live aboveground biomass, standing dead trees, dead and down wood, understory vegetation, harvested wood products, vegetative litter and soil. Figure 1 shows the basic carbon biogeochemical cycle for Sierra Nevada forests while Table 1 shows the typical allocation of carbon pools in a Sierra Nevada mixed conifer forest, the dominant forest type in the Sierra Nevada. The amount of carbon stored in each pool is referred to as a carbon stock. Carbon stocks are usually measured in units of millions of metric tons carbon dioxide equivalent (MMT CO₂e) or Teragrams (Tg or 10¹²) of carbon CO₂, which are equivalent. One mass unit of carbon is equivalent to 3.667 mass units of CO₂. In addition to the amount of CO₂ stored above and below ground in soil and biomass, the Sierra Nevada sequesters additional carbon from the atmosphere as trees and plants perform photosynthesis and build biomass (Forest Climate Action Team 2018a).

The rate by which the mass of the carbon stock changes per unit area over time is the carbon flux. Carbon fluxes are associated with a specific direction, or the transfer of carbon from one carbon pool to another. Fluxes between pools collectively determine the overall carbon biogeochemical cycling in the Sierra Nevada. As carbon is transferred from the live pool to the dead pool, it will eventually either decay or burn and be emitted into the atmosphere. Therefore, understanding the fluxes of carbon from the live to dead pool as a result of climate driven disturbances (e.g., wildfires, drought, disease and pests) is needed to predict future carbon stocks in the Sierra Nevada.

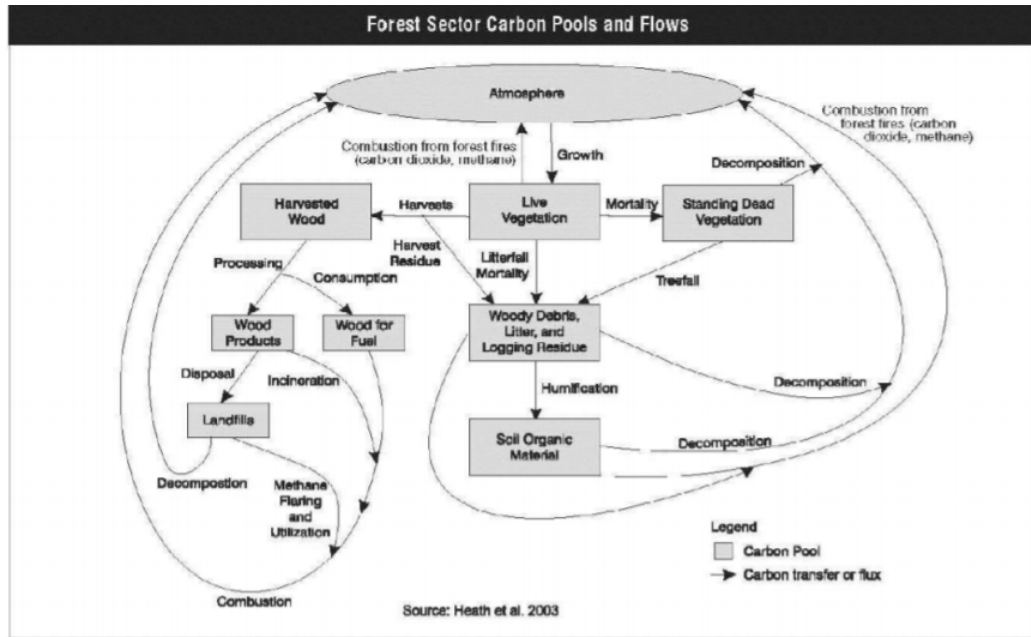


Figure 1: The various carbon pools and fluxes in Sierra Nevada forests. From Heath et al. (2003).

Table 1: Average distribution of forest carbon in tons per acre for mixed conifer forest. Forest carbon in tons per acre from common western forest types, including California mixed conifer forests. These numbers represent an average of USFS and private mixed conifer forests in California. From Stewart et al. (2011).

Forest Component	Live tree	Soil	Forest floor	Dead/ Down	Dead tree	Under story	Total
Tons of carbon per acre	55	22	17	8	5	1	107
Percent of total carbon per acre	51%	21%	16%	7%	4%	1%	100%

The Net Carbon Ecosystem Balance (NCEB) is the total net gain or loss of organic carbon in an ecosystem regardless of temporal or spatial scale and is a type of carbon flux. A positive NCEB represents a carbon sink that is accumulating more carbon, while a negative NCEB is associated with a carbon source that emits carbon into the atmosphere. Understanding the magnitude of carbon stocks and fluxes is important for carbon accounting and estimating the NCEB and the carbon sequestration potential of a particular forest over time (Liang et al. 2017). NCEB is a simple metric that can be standardized across many different ecosystems and used at various temporal and spatial scales. This paper focuses on the NCEB as the clearest metric for answering the paper's overarching research question of how the Sierra Nevada can be maintained as a carbon sink over the long-term.

Currently, the Sierra Nevada remains an important carbon sink, but without careful management and a substantial increase in thinning and prescribed burning treatments it will become a major source of

emissions, exacerbating global climate change. Sierra Nevada forests are at an ecological tipping point of irreversible transformation. Wildfires, drought, and bark beetles are driving unprecedented mortality in Sierra Nevada forests. Between 2010 and 2017, over 129 million trees died in the Sierra Nevada from a combination of drought and bark beetles (Forest Climate Action Team 2018). From 2014-2017, an estimated average of 48.9% of trees in Eldorado, Sequoia, Sierra and Stanislaus National Forests died (Fettig et al. 2019). The largest and most destructive wildfires in the state's history in terms of acres burned, property damage, and fatalities have all occurred within the last five years. In 2020, wildfire emissions totaled 25% of California's total greenhouse gas (ghg) emissions (CARB 2020a). Much of the area burned at such high severity that it is unlikely to support natural forest regeneration and will gradually transition from coniferous forest to chaparral scrubland, which stores less than 10% of the carbon of the forests it replaces (Gonzalez et al. 2015).

These changes have massive implications for the NCEB of the Sierra Nevada and California's ambitious emission reduction goals. Wildfire, drought and bark beetle driven mortality will negatively impact the overall NCEB of the Sierra Nevada by transferring massive amounts of carbon to unstable pools likely to be emitted to the atmosphere through either decay or combustion in the near future. For example, the carbon moved to the dead pool from dead trees in the Southern Sierra in 2016 alone was 52MMT CO₂e, greater than the emission reductions from California's economy in the previous 3 years combined (Sierra Nevada Conservancy 2019). Maintaining the long-term stability of existing carbon pools should be the overall goal for carbon management in the Sierra Nevada, not maximizing annual net carbon sequestration. California will be unable to meet its ghg reduction goals without ensuring the long-term viability of the Sierra Nevada as a carbon sink.

Estimates of Sierra Nevada carbon stocks vary widely depending on the assessment methodology and which carbon pools are accounted for. Few comprehensive published estimates specific to the Sierra Nevada bioregion exist, so larger studies covering the entire State of California were also considered. However, even the lowest end of the range of estimates (3,119 MMT CO₂e for all aboveground biomass in California) shows that the amount of carbon stored in the Sierra Nevada is significant and will affect California's ability to meet its ghg reduction goals. Multiple lines of evidence are presented to demonstrate the efficacy of thinning and prescribed burning treatments including direct measurement studies and modeled simulations using the Landis II platform. Treatment impacts on basal area, stand density, species composition, wildfire mortality vulnerability and wildfire severity and spread are

measured across numerous ecosystems, geographies, and timespans to establish how treatments alter forest dynamics to increase resiliency to wildfires, drought, and bark beetles.

Thinning, prescribed burning and reforestation treatments can increase the Sierra Nevada's overall resiliency to these existential threats. However, the current pace and scale of treatments is a fraction of what is needed to maintain the Sierra Nevada as a long-term net carbon sink. Approximately 300,000 acres per year in the Sierra Nevada would need to be treated to attain overall forest resilience goals. While this endeavor would conservatively cost around \$300 million per year, the cobenefits of treatments would cover the cost of treatments and yield a substantial return on investment. Cobenefits include protection of life and property, improved air and water quality, and better economic opportunities for underserved gateway communities and were valued at a total of \$61.551 billion in 2018, meaning that the anticipated cost to treat the required acreage is just under 5% of the total value of the cobenefits. Wildfires caused tens of billions in property damages in the Sierra Nevada in 2018 and 2020 (Roman et al. 2020). Preventing even a single destructive megafire would pay for itself instantly. Removing barriers to treatments by increasing public funding, streamlining environmental regulations, and developing private markets for waste byproducts can accelerate the pace and scale of treatments.

Funding a federal Civilian Climate Corps to directly implement thinning and prescribed burning treatments would help maintain the Sierra Nevada as a net carbon sink while realizing several significant cobenefits. The time for such a program is ripe, with a proposed \$1.9 trillion infrastructure bill currently being discussed in Congress. President Biden's infrastructure bill, or the American Jobs Plan, specifically calls for funding to protect Americans from extreme wildfires (The White House 2021). In addition, on January 27, 2021 President Biden signed an "Tackling the Climate Crisis at Home and Abroad" which directs the federal government to "put a new generation of Americans to work conserving and restoring public lands and waters, increasing reforestation, increasing carbon sequestration in the agricultural sector, protecting biodiversity, improving access to recreation, and addressing the changing climate."

The goal of this paper is to examine the importance of the Sierra Nevada region as a carbon sink and elucidate how thinning, prescribed fire and reforestation treatments can be used to maintain the Sierra Nevada as a net carbon sink over the long-term. The paper begins with a literature review of carbon stock and carbon flux estimations for the Sierra Nevada and California to determine how much carbon is currently stored in the Sierra Nevada and whether it is currently a net sink or source of emissions. Next,

the paper details how thinning, prescribed fire and reforestation treatments can improve the overall long-term stability of the Sierra Nevada region by increasing resilience to the most significant drivers of tree mortality in the Sierra Nevada, wildfires, drought, and bark beetles. A summary of the cobenefits of these treatments is then presented along with an analysis of the most significant barriers to increasing the adoption of treatments on the landscape. Finally, environmental management recommendations for eliminating barriers and dramatically increasing the pace and scale of treatments are presented.

II. Methods

This paper includes literature reviews of direct measurement and modeled simulation studies of carbon biogeochemical cycling in the Sierra Nevada. Additionally, literature reviews of the cobenefits of and barriers to thinning, prescribed fire and reforestation treatments in the Sierra Nevada were completed. With the exception of the intrinsic value cobenefit, cobenefits with published economic valuation analyses were selected so a comparison to the costs of treatments could be made. Interviews with practicing professionals, including a professor, environmental consultant, and USFS Fire Management Officer were conducted to identify key barriers to implementing thinning and prescribed burning treatments and potential solutions. The interview participants were chosen because they represent a cross section of the influencers and decision makers responsible for implementing treatments.

To further narrow the scope of studies assessed in the literature review of carbon biogeochemical cycling, features of high-quality studies were identified. Features of high-quality total carbon stock estimates include high temporal and spatial resolution, evaluation of all carbon pools, confidence intervals and uncertainty analysis, verification against direct measurements using regression analysis and comparison against previously published values. It is also important for studies attempting to quantify carbon flux post fire disturbance to extend beyond 5 years after the treatment because shorter time periods may produce misleading results (Powers et al. 2013; Dore et al. 2016). Using these criteria, robust carbon stock assessment methodologies are identified in Table 2, even if the study did not publish a specific estimate for the Sierra Nevada region.

III. Estimating the Net Carbon Ecosystem Balance and carbon flux of the Sierra Nevada

3.1 Net Carbon Ecosystem Balance estimations in the Sierra Nevada

Precisely quantifying the amount of total carbon stored in the Sierra Nevada is critical to understanding its importance as a long-term carbon sink and potential climate carbon sequestration solution. Without accurate carbon stock and flux estimates, the relative benefit of ecological forest management regimes that help maintain a stable, positive long-term NCEB in the Sierra Nevada cannot be compared to anthropogenic ghg emissions or other potential climate change mitigation solutions.

The only publicly available comprehensive estimate for total carbon stocks in the Sierra Nevada that includes both above and below ground carbon pools was 3,498 MMT CO₂e (Christensen et al., 2017). For comparison, total anthropogenic ghg emissions for the entire State of California was 425 MMT CO₂e in 2018, the most recent year for which a comprehensive estimate was available (CARB 2020). The 3,498 MMT CO₂e estimate was published by the Forest Climate Action Team in the California Forest Carbon Plan (Forest Climate Action Team 2018). The Forest Climate Action Team is an interagency workgroup comprised of local, state and federal government agencies that was formed in 2014 to develop a plan for managing California's forests as carbon sinks. Forest Climate Action Team's Sierra Nevada carbon stock estimates were derived from the AB 1504 California Forest Ecosystem and Harvested Wood Product Carbon Inventory: 2006 – 2015 (Christensen et al. 2017). Christensen et al. (2017) used direct measurement data from the Forest Inventory and Analysis program and applied a traditional "stratify and multiply" approach. Estimates for each carbon pool and forest type were prepared and then multiplied by the areal extent of each forest type. This study stands out in that it includes all potential carbon pools: above ground live tree, above ground standing dead trees, understory vegetation, down wood, vegetative litter, below ground live and standing dead trees and soil carbon and publishes a specific estimate for the Sierra Nevada.

Methodologies for estimating carbon stocks in the Sierra Nevada can be classified broadly into two categories: direct measurements from closely monitored field test plots combined with a "stratify and multiply" approach and remote sensing modeling. Most estimations of Sierra Nevada forest carbon stocks rely on underlying data from the United States Forest Service's Forest Inventory and Analysis program. The Forest Inventory and Analysis program was created in 1928 to inventory and monitor the

Nation's forests via a network of approximately one-acre test plots distributed at a spacing of about one plot for every 2400 ha. There are 16,665 plots across California and 20% of all plots have been surveyed each year since 1997. For each test plot, the Forest Inventory and Analysis program meticulously collects data on the number and species of trees, tree height, diameter, health, mortality, and disturbances such as wildfires and bark beetle infestations (Blackard et al. 2008; USFS FIA 2021). Data collected from Forest Inventory Analysis program plots is often used to validate estimates derived from remote sensing methodologies.

There is a wide divergence in estimates for the ratio between carbon stored aboveground versus belowground. Belowground carbon stocks are usually estimated by taking direct measurements of various forest floor and below ground pools and measuring the amount of carbon via combustion in a controlled laboratory setting. Some studies differentiate between roots, woody debris, and organic soil carbon, while others lump them all in together in one belowground carbon pool. Some estimates include surface fuels such as vegetative litter and duff, while others only include organic soil carbon. Estimates of the ratio of belowground carbon to aboveground carbon vary from 21% to 49% (Sleeter et al. 2015; Stewart et al. 2011; Wiechmann et al. 2015; Christensen et al. 2017). The uncertainty around soil carbon pools leads to significantly different estimates of total carbon stocks in the Sierra Nevada.

Estimating the total amount of above ground carbon in a forest begins with accurately measuring the number and dry weight of all trees. It is well documented that about 50% of the dry weight of a tree is made up of carbon (Brown and Lugo 1982). Live trees are the largest pool of aboveground carbon. Allometric equations are used to estimate the biomass of a tree based on the diameter measured at breast height, the species of tree and tree height. The equations can be improved by including more variables such as wood density and shape to estimate an individual tree's aboveground biomass more accurately, but this is not practical on a landscape level (Forest Climate Action Team 2018b).

Remote sensing methodologies are best suited to scale carbon stock and flux estimations to the landscape or ecosystem level (Gonzalez et al. 2015; Blackard et al. 2008; Battles et al. 2014). Remote sensing uses satellite or aerial imagery data to classify vegetation types, heights, densities, and other attributes. Modeling techniques are then used to estimate the aboveground carbon density for each vegetation classification. Finally, the estimated density of each classification is multiplied by its areal extent. Battles et al. (2014) completed a comprehensive inventory of carbon sequestration and emission

on California's forests and rangelands, excluding below ground carbon in soil, using remote sensing data from the United States Geological Survey's Landscape Fire and Resource Management Planning Tool (Landfire). The Landfire dataset provides 163 different vegetation types, 39 height classes and 54 cover classes for California. Data from the USFS Forest Inventory and Analysis program and the National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer dataset were then used to calculate carbon densities for each unique spatial unit identified by Landfire's vegetation type, height class and cover class. The study concluded that between 2001 and 2008 the total stock of all aboveground carbon in California forests and rangelands decreased from 9,542 to 9,175 MMT CO₂e, or a decrease of roughly 41 MMT CO₂e per year (Battles et al. 2014).

Gonzalez et al. (2015) used the same methodology as Battles et al. (2014) but had a slightly different analysis area as it included all terrestrial carbon in California, excluding urban and agricultural areas. Blackard et al. (2008) estimated U.S. forest biomass using FIA plot data, landcover data from the National Land Cover Dataset and satellite imagery from NASA's MODIS dataset. The U.S. was divided into 65 ecologically similar zones, one of which closely mirrored the Sierra Nevada region. Each region was classified using 250m resolution pixels that estimated carbon density and compared modeled estimates against estimates from direct measurements and allometric equations on USFS FIA plots (Blackard et al. 2008).

Although these remote sensing modeling approaches differ, they share the same inherent challenges. Low spatial and temporal resolution and misclassification of vegetation increase uncertainty. Different remote sensing technologies having varying degrees of accuracy for classifying vegetation by height, density, fractional cover and other attributes. Some can measure these attributes as continuous variables at spatial resolutions as low as 1m, whereas others divide all vegetation types into as few as three categories. The resolution of each stock assessment methodology is included in Table 2 below. Most studies omit estimates of more difficult to measure carbon pools such as vegetative litter, soil carbon and other below ground carbon pools.

Table 2: Studies Estimating Total Sierra Nevada Carbon Stocks*Estimates of carbon stocks from all studies were converted to MMT CO₂e for ease of comparison.*

Study and Year Published	Total C Stock Estimate (MMT CO ₂ e)	Above ground estimate (MMT CO ₂ e)	Below ground estimate (MMT CO ₂ e)	Total C Stock estimate for all of California (MMT CO ₂ e)	Summary of Methodology	Year(s) of estimation	Resolution	95% CI included?
(Christensen et al. 2017)	3,498.251 (+/-42.986)	2,200.198	1,298.053	12,100 (+/-100) Estimate includes all forestland in CA.	Direct measurement data from the FIA. Stratify and multiply approach.	2006-2015	<1m	Yes
Sierra Nevada Conservancy (2012)	NA	380.343	Did not assess.		The author used the MODIS remote sensing methodology developed by Blackard et al. (2008) to estimate total aboveground biomass. A subset of this data was used for the estimate.	1990-2003	250m	Not reported.
(Gonzalez et al. 2015)	NA	NA	NA	3,119.5 Estimate is for all terrestrial biomass in CA except agriculture and urban areas.	Same as Battles et al. 2014.	2010	30m	+/- 844
Battles et al. (2014)	NA	NA	NA	9,175 (All forest and rangelands in CA). Excludes below ground carbon.	Remote sensing using USGS Landfire database.	2008	30m	+/- 95.42 MMT CO ₂ e

Surprisingly few Sierra Nevada NCEB estimates have been published and no comprehensive meta-analysis of estimates exists. Only one comprehensive estimate of total above and below ground carbon stocks had a section dedicated exclusively to the Sierra Nevada, so extrapolations from larger data sets and published analyses are necessary to provide a greater number of estimates for comparison (Christensen et al. 2017). Comparing different carbon stock estimates is difficult because they differ in their geographic and temporal boundaries as well as which carbon pools are included or excluded. For example, Gonzalez et al.'s (2015) estimate includes aboveground biomass in all wildlands (forests, wetlands, rangelands) but excluded dead wood and vegetative litter while Christensen et al.'s estimate included below ground carbon as well. While the data exists to perform an estimate of total carbon stocks of above ground and below ground carbon pools in the Sierra Nevada, few published estimates exist.

3.2 Annual Carbon Absorption Capacity of the Sierra Nevada

In addition to the carbon already stored in Sierra Nevada forests, the Sierra Nevada may also sequester additional carbon from the atmosphere each year, offsetting anthropogenic ghg emissions. Methods for measuring the net annual sequestration or flux vary and produce different results. No consensus exists on whether the Sierra Nevada has already become a net source of emissions or remains a net sink. Estimates for the annual net sequestration of Sierra Nevada forests range from 8.7 to -51 MMT CO₂e (Christensen et al. 2017; Battles et al. 2014). As with carbon stock estimations, the difference in methodology largely accounts for the difference in flux estimates. Regardless of the current carbon flux, existing Sierra Nevada carbon stocks are significant and climate driven disturbances such as wildfires, drought, and bark beetle infestations have the potential to emit devastating amounts of carbon currently sequestered in stable pools and biomass into the atmosphere, thus further exacerbating climate change.

3.2.1 Evidence that the Sierra Nevada is a net source of emissions

Battles et al. (2014) estimated a net decrease of 367 MMT CO₂e in total California forest carbon stocks between 2001 and 2008. Gonzalez used the same remote sensing methodology and underlying USGS Landfire dataset as Battles et al. (2008). Gonzalez et al. (2015) estimated aboveground carbon stocks of all California wildlands (wetlands, forests and grasslands) and concluded that carbon stocks decreased by 69 MMT CO₂e +/- 15 between 2001 and 2010, suggesting that the Sierra Nevada may already be a net carbon source of emissions. The decrease in carbon stocks was mostly due to a decrease in carbon

density in areas burned by severe wildfires. Overall, the authors concluded that two-thirds of the net aboveground carbon stock loss occurred on less than 6% of the analysis area that had been burned.

High intensity, severe wildfires drive landscape cover change as areas once dominated by mixed conifer forests are replaced by bushy chaparral scrubland. Mixed conifer forests, which are the most abundant forest type in California, cover over 7.8 million acres of land and comprise around 24% of all California forests and have an average carbon density of 107 metric tons of CO₂ per acre (Christensen et al. 2016). Chaparral scrubland stores only about 10% of the carbon that the forests it is replacing stored (Gonzalez et al. 2015). Furthermore, once these areas burn the vegetation that succeeds the landscape is at greater risk of burning at a higher severity, which increases the likelihood the forest landcover will not be regenerated and will be replaced by shrubland or grassland (Coppoletta et al. 2016). After a severe wildfire, stands of dead trees gradually lose limbs and fall to the ground. When combined with non-fire adapted shrubs that commonly take root after a disturbance, the new ecosystem is more likely to reburn at a high severity 5-15 years after the initial burn. Whether the reburn is a lower-severity or high severity burn helps determine whether the forest will regenerate or be converted to a shrubland or grassland ecosystem (*Figure 2*).

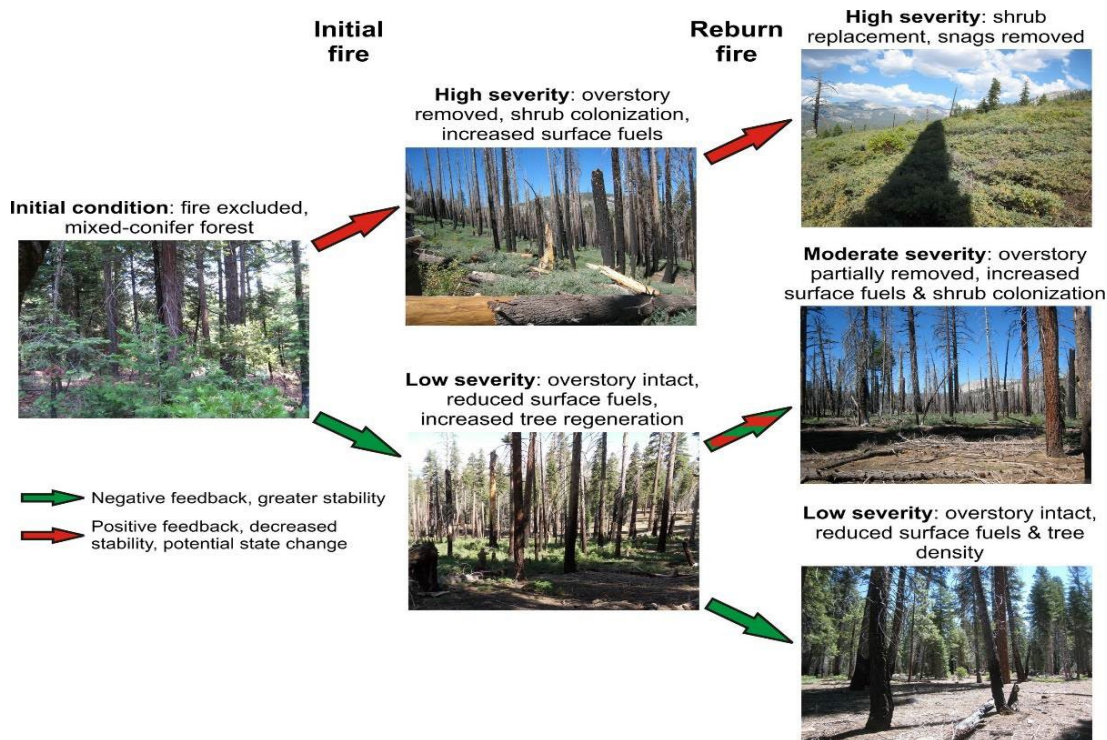


Figure 2: A conceptual model of post high-intensity wildfire revegetation in a Sierra-mixed conifer forest. The model shows that vegetation composition affects reburn severity which determines eventual ecosystem composition post disturbance. From Coppoletta et al. (2016).

Both remote sensing studies excluded below ground carbon in soil as remote sensing cannot capture carbon stored in the below ground, vegetative litter, and downed wood pools. Other limitations of these remote sensing studies include undercounting tree growth in carbon dense mature forests such as Giant Sequoias or Coastal Redwoods and errors in vegetation classification, especially concerning standing dead carbon pools (Gonzalez et al. 2015). Sierra Nevada forests along with Coastal Redwood forests in Northern California, have the greatest terrestrial biomass density in California with Giant Sequoia ecosystems in the Sierra Nevada reaching densities of 2200 Mg C ha⁻¹ (Blackard et al. 2008). While neither study includes carbon flux estimates specific to the Sierra Nevada, these overall estimates for California both concluded that total forest carbon stocks had decreased by 41 and 7.6 MMT CO₂e, respectively. These decreases in total forest carbon stocks suggest the Sierra Nevada is a net carbon source or at best, sequesters negligible amounts of carbon.

3.2.2 Evidence that the Sierra Nevada is a net carbon sink

Christensen et al. (2017) applied a comprehensive approach to estimating net carbon flux across California by considering above ground and below ground carbon pools and employing protocols established in the literature to estimate each pool. Christensen et al. (2017) concluded the Sierra Nevada sequestered an average of 8.7 MMT CO₂e each year between 2006 and 2015. The study included estimates for the aboveground live tree, aboveground standing dead tree, aboveground down wood, aboveground and below ground understory vegetation, roots, vegetative litter and soil pools, but excluded the harvested wood products pool. The estimation relies on direct measurement data, mostly from the USFS Forest Inventory and Analysis program and allometric equations versus remote sensing data and is a 10-year average based on plots and trees initially measured between 2001 and 2005 then re-measured 10 years later between 2011 and 2015. The study also accounts for changes in landcover between forested and non-forested categories and non CO₂ ghg emissions from wildfires such as black carbon.

3.2.3 Explanation of differences in Sierra Nevada carbon flux estimates

There are tradeoffs between the two methodologies discussed for estimating carbon fluxes. Ground level measurements at fixed plots over time provide the most accurate assessments of carbon fluxes but are limited to sites with monitored test plots and are not as scalable as remote sensing estimates. Overall, Christensen et al.'s (2017) study is more comprehensive than the remote sensing studies that only include aboveground carbon (Gonzalez et al. 2015; Battles et al. 2014).

Studies have estimated that 21% of carbon stocks of Sierra Nevada mixed conifer forests is stored in below ground soil pool (Sierra Nevada Conservancy 2012). However, estimates of soil carbon's effect on net sequestration is minimal and was estimated at .8 MMT CO₂e +/- .5 (Christensen et al. 2017). This number represents the amount of additional carbon taken from the atmosphere and stored in soils throughout the Sierra Nevada in a typical year. Mixed conifer forests are the largest carbon stock, both statewide and in the Sierra Nevada (Figure 2). Because the study was based on direct measurements from USFS Forest Inventory and Analysis program plots, it more accurately captures changes in tree height, an important component of net carbon flux calculations (Holland et al. 2019).

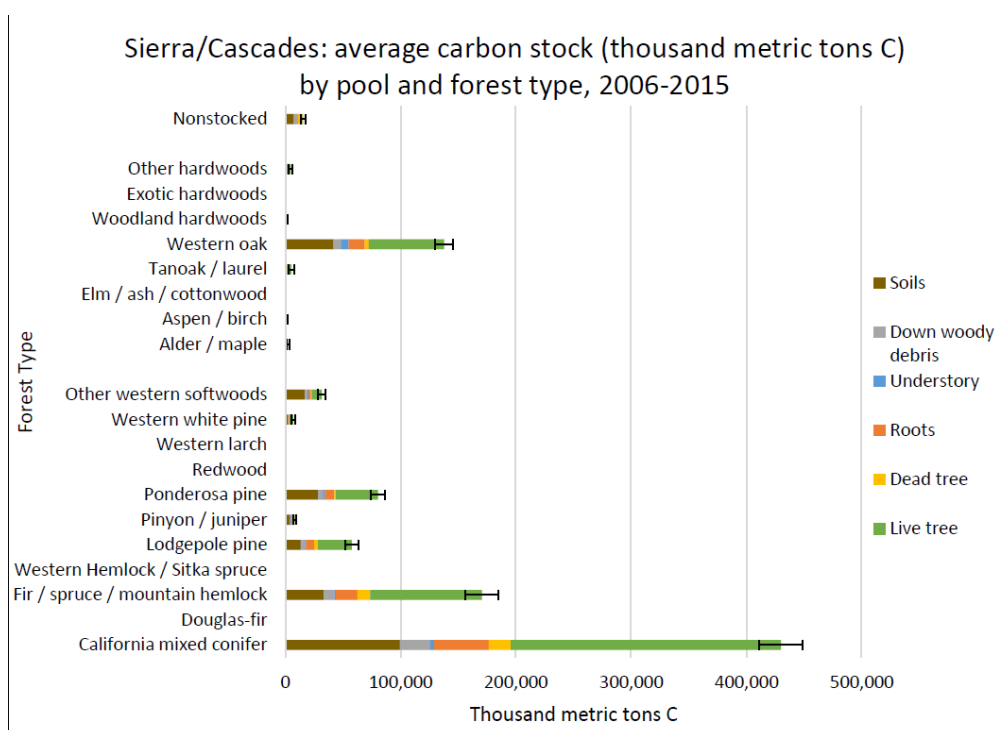


Figure 3: The estimated carbon stock for each carbon pool by forest type. California mixed conifer forests are the most significant carbon sink. From Christensen et al. (2017).

Regardless of whether the Sierra Nevada is currently sequestering or emitting carbon, the range of all estimates suggests that its potential as a climate mitigation solution is very limited. Even the most optimistic estimates of net sequestration are less than 2% of California's total ghg emissions (Christensen et al. 2017). Sierra Nevada forests are likely at their carbon storage peak and are expected to emit carbon as droughts, wildfires and pests drive cataclysmic mass mortality events. This is because the Sierra Nevada is far denser now than it was a hundred years ago due largely to a century of fire suppression policy that has led to an unprecedented buildup of fuels (Stephens et al. 2007). Therefore,

the goal of the forest management regimes is not to manage Sierra Nevada forests to maximize carbon sequestration, but rather to stabilize the substantial remaining live carbon stocks. Section IV of this paper will discuss how various forest management regimes can assist the Sierra Nevada adapt to new climactic conditions that threaten the long-term stability of existing carbon stocks.

Table 3: Studies estimating whether Sierra Nevada is an annual carbon source or sink

Study and Year Published	Annual Carbon Flux Estimate (MMT CO ₂ e)	Year(s) of Estimation	Net Source or Sink?	Analysis Area	Methodology	Study Quality
(Christensen et al. 2017)	+8.7+/-3	2006-2015	Sink	Sierra Nevada	FIA plot analysis, allometry	High
(Gonzalez et al. 2015)	-.8 +/- .2%	2001-2010	Source	All California wildlands (forests, grasslands, wetlands)	Remote sensing modeling using USGS Landfire database. Below ground carbon pools were not included in this analysis.	Medium
Battles et al. (2014)	-51 +/- 3.7	2001-2008	Source	All California forests and rangelands.	Remote sensing modeling using USGS Landfire database, FIA data and NASA MODIS dataset to estimate carbon densities of unique spatial units. Below ground carbon was not included.	Medium

*Note a positive carbon flux indicates net sequestration and addition of biomass while a negative flux represents net emissions to the atmosphere. Units presented in this table were converted into MMT CO₂e for ease of comparison.

3.3 Potential emissions from Sierra Nevada Forests if no action is taken

The Sierra Nevada region stores an immense amount of carbon in its biomass and soil and may even sequester additional carbon annually, but without adequate forest management this carbon stock is at risk of being emitted to the atmosphere. Stabilizing existing carbon stocks in the Sierra Nevada over the long-term is essential to meeting California's ambitious ghg emission reduction goals. Without intervention, mass tree mortality in the Sierra Nevada driven by climate related disruptions (e.g., bark beetles, wildfires and drought) will shift carbon from stable pools to destabilized pools, negatively impacting long-term NCEB. Stable carbon pools are stocks of carbon that are not at risk of being transferred to the atmosphere through decomposition, combustion, or landscape cover change driven by climate change. Various forest management regimes can help stabilize carbon pools over the long-term by promoting better forest health and resilience to drought, pests, fire, and disease.

In recent years, significant amounts of biomass have been transferred from stable pools to destabilized pools that will eventually be released into the atmosphere. For example, the carbon moved to the dead pool from dead trees in the Southern Sierra in 2016 alone was 52MMT CO₂e, greater than the emission reductions from California's economy in the previous 3 years combined (Sierra Nevada Conservancy 2019; Forest Climate Action Team 2018). For comparison, this means California could reduce its ghg emissions from all electricity generation by 82% overnight and the net benefit would be cancelled out by tree mortality in one year in the Southern Sierra Nevada. An increase in dead and down trees increases fuel loads, which leads to greater risk of high severity fires. High severity fires represent the greatest threat to maintaining a positive NCEB over the long-term. Total ghg emissions for all wildfires in California from 2000-2019 averaged 14 MMT CO₂e per year but peaked at 40 MMT CO₂e in 2018. In 2020, a record 112 MMT CO₂e or more than 25% total anthropogenic emissions, was emitted from wildfires across California (CARB 2020b).

Soil carbon pools are also negatively affected by largescale mortality and high severity wildfires. In fact, immediate CO₂ emissions from combustion during a wildfire may represent as little as 15% of the total emissions as dead trees continue to decompose for several years (Sierra Nevada Conservancy 2017). Soil carbon availability varies across the severity of a burn gradient, with areas experiencing high severity fire storing less carbon than areas burned at a moderate or low severity. Additionally, essential nutrients

such as N and C stored in shallow surface soils can be depleted during high severity fires, which restricts forest regeneration (Adkins et al. 2019).

High severity fires also drive landscape cover change from high to low density carbon ecosystems after a fire. Even under ideal circumstances in which a forest is restored after a wildfire, it can take decades for mature trees to reestablish themselves with NCEB comparable to pre disturbance levels. As fires burn Ponderosa and Sugarpine trees killed by bark beetles in the lower elevation bands of the Sierra Nevada (914m-1524m), there is evidence that the forest succession is not occurring, and the ecosystem is shifting towards a chaparral scrubland (Long and Quinn-Davidson 2014).

Current rates of conifer forest regeneration post wildfire disturbance have shown alarming trends for California's NCEB. A study of 1490 research plots, over 10 different National Forests representing a diverse array of Sierra Nevada forest types and structures, studied over 15 years showed that after 11 years, 43% of research plots had no conifer regrowth and another 11% had only a single conifer (Welch et al. 2016). Observations were made between 5 and 11 years post wildfire disturbance. This study was unique in its size, longevity and diversity of forest systems captured. The overall conclusions were that forest regeneration is not occurring 50% of the time and that when it was occurring, it was not sufficient to meet USFS stocking guidelines, which are used to determine whether a forest can support a commercial timber harvest. Most conifer regeneration that did occur were shade-tolerant fire-intolerant species, meaning that they will be vulnerable to future high severity wildfires that will negatively impact the NCEB of the forest (Welch et al. 2016).

Without any intervention and following business as usual, estimates of future NCEB in the Sierra Nevada over the next several centuries are bleak. Over the next 590 years Liang et al. (2017) predicted a 73% reduction in NCEB in Sierra Nevada mountains, turning the region from a carbon sink into a carbon source. The reduction in NCEB was attributed to changes in landscape cover from failed forest regrowth. Changing temperature and precipitation patterns are expected to drive this vegetation conversion (Liang et al. 2017). Another model simulating ecosystem carbon trends in the Lake Tahoe Basin between 2010 and 2100 also predicted climate change would reduce the amount of carbon stored in the ecosystem. Drought, bark beetle infestations, and wildfires were key drivers. The density of host trees and the type of forest management regime were identified as important contributors not linked to

climate change. The model also showed that current fuel management practices were insufficient to ameliorate NCEB reductions (Scheller *et al.* 2018).

The expert elicitation methodology has also been used to produce an estimate of reductions in aboveground carbon stocks in the Sierra Nevada from 2030 through 2100. Using surveys of from 75 experts, Lalonde *et al.* (2018) concluded the median result was a modest 8% decline in carbon stocks by 2100 assuming conventional forest management regimes continue (Lalonde *et al.* 2018). Forest management regimes such as thinning, harvest and prescribed fire were predicted to outperform conventional management by 11% at best, suggesting a very limited impact on overall ghg reduction goals. The main problem with this study is that it focuses on the sequestration potential of Sierra Nevada forests instead of evaluating potential carbon stock losses.

If carbon stocks in the Sierra Nevada continue to experience massive fluxes driven by climate related disturbances such as wildfire and bark beetle infestations, our greatest terrestrial carbon sink can produce emissions that dwarf even the largest ghg emission reduction efforts. For example, ghg emissions from all passenger cars in California totaled 119 MMT CO₂e in 2018 (CARB 2020). This is roughly equivalent to total wildfire emissions in 2020. We can rapidly electrify our transportation and electricity generation sectors, but still miss our ghg reduction goals if the vast amount of carbon stored in the Sierra Nevada is emitted through combustion or mortality. Ensuring the Sierra Nevada maintains a positive NCEB over the long-term is essential to meeting our ghg reduction goals and combating climate change.

IV. How forest management can help maintain the Sierra Nevada as a long-term carbon sink

Sierra Nevada forests are vastly different today than prior to the advent of modern forest management beginning in the early 19th century in terms of stand density, species composition and ultimately the total NCEB of the region (Foster *et al.* 2020). Historically, Sierra Nevada landscapes were adapted to frequent low severity fires that periodically reduced fuel loads and limited large, high severity stand replacing fires (Stephens *et al.* 2007). Exclusion of fire from the landscape through a century of fire suppression has led to denser forests and a higher total NCEB. Sierra Nevada forests are likely approaching their peak carbon carrying capacity as forests cannot get much denser and there is limited land available for additional growth (D. Saah, USF, pers. comm.). Therefore, forest management

treatments aimed at protecting the Sierra Nevada as a carbon sink should not focus on incrementally increasing the amount of additional carbon sequestered annually, but rather focus on protecting or stabilizing the large stocks of existing carbon in aboveground live biomass and soil. Stable pools of carbon are pools that are not at risk of being disproportionately transferred to dead pools or the atmosphere through combustion, disease, premature mortality, pests, drought or climate change. Stabilizing carbon pools in the Sierra Nevada can be achieved by fostering healthy and resilient forests with thinning, prescribed fire and reforestation treatments.

Maintaining a positive NCEB in the Sierra Nevada over the next 10, 20 and even 100 years will require extensive forest management treatments on the landscape including various methods of thinning, prescribed fire, and reforestation. Thinning refers to the hand or mechanical removal of vegetation, smaller diameter trees or lower tree limbs that serve as ladder fuels. Figure 4 below shows the clear difference between forest that has been thinned and forest that remains at a density above its pre-colonial average. Prescribed burning is the practice of intentionally igniting fires to reduce hazardous fuels such as vegetation, vegetative litter and duff, dead and downed wood and small diameter live trees. Prescribed burns are applied to reduce the risk of high severity wildfires in the future and create defensible space around buildings and other assets. Thinning treatments are often a prerequisite to prescribed fire treatments because a forest must be thinned prior to igniting a controlled burn to ensure that the burn can be managed and extinguished. Reforestation treatments are used to accelerate forest regeneration after major disturbances and to influence the stand structure, species composition, landscape cover and ultimately, the total NCEB of a forest. Planting additional seedlings, applying herbicides to kill noxious weeds and invasive species, and removing undesirable species are examples of reforestation treatments.



Figure 4: Forest treated with mechanical thinning (left) and an untreated forest (right), in the central Sierra Nevada. The treated area has lower basal area and density compared to the untreated area.
Photo Credit Martha Conklin

These treatments are often used in combination with each other to maximize carbon stabilization benefits as well as a range of other forest management goals such as water storage, sustainable timber harvest, improved wildlife habitat and recreational access. The overarching goal of these treatments is to alter the forest's stand structure, density, species composition and fire regime to increase forest resiliency to wildfires, pests, droughts, landcover change and other disturbances.

4.1 Evidence that forest management can maintain the Sierra Nevada as a carbon sink

Promoting forest resiliency to effectively manage Sierra Nevada forests as carbon sinks over the long-term has garnered significant research attention in recent years. This section presents multiple lines of evidence to demonstrate that thinning, prescribed burning and reforestation treatments can create healthier forests that are more resilient to the top threats to carbon stability in the Sierra Nevada: extreme wildfires, drought, and bark beetles. Three lines of evidence are presented: direct measurement studies on controlled test plots (Stephens et al. 2009; Wiechmann et al. 2015), modeled simulations using the Landis platform (Shuang Liang et al. 2018; Krofcheck et al. 2017; Loudermilk et al. 2017; Hurteau 2017) and studies examining the impact of treatments on mitigating drought and bark beetle driven tree mortality (Fettig et al. 2019; Restaino et al. 2019; van Mantgem et al. 2016; Young et al. 2017).

Treatments increase stability of carbon stocks by altering forest structure to create forests that have lower stand densities, more large diameter trees, fewer fire intolerant species and are more heterogenous. They also change fire regimes by reintroducing low-severity surface fire to the ecosystem. Treatments that alter forest composition, stand density, fire regimes and carbon dynamics to replicate these characteristics can therefore increase carbon stability in the long-term. This is because less dense forests that burn more frequently and less intensely are more resilient to extreme wildfires, drought, and bark beetle infestations. Forests with these characteristics are more likely to maintain a positive NCEB over the long-term.

4.1.1 Direct measurement studies

Direct measurement studies involve the application of various fuels management and restoration treatments to test plots throughout the Sierra Nevada to examine the effect on future wildfire severity, carbon flux, NCEB, forest regeneration, forest composition, overall resiliency, and many other outcomes. Most forest management treatments increase CO₂ emissions or decrease carbon stocks in the short-

term, but help stabilize carbon stocks over the long term by reducing the likelihood of high severity, stand replacing wildfires that result in landscape cover change from higher carbon density ecosystems such as mixed conifer forests to lower carbon density ecosystems, such as chaparral scrub (Coppoletta et al. 2016). A study involving mechanical thinning, prescribed burn and a combination of thinning and prescribed burn treatments at twelve test plots totaling 225 ha in Eldorado National Forest in the Sierra Nevada from 2000-2005 underscores this point.

Stephens et al. (2009) evaluated each treatment's impact on total carbon stocks and concluded that while the 90% of the aboveground live carbon in the control plots had a 75% or greater chance of being killed during a severe wildfire, the treated plots were significantly more fire resilient because they created low density stands of large fire resistant pine trees. Figure 5 shows the difference in resilience to fire severity between the three treatment applications and the control. Although treatments reduced total carbon stocks in the short term by thinning and burning understory vegetation and surface fuels, which accounted for about 14% of the total live carbon in aboveground pools, they more than made up for these temporary decreases by increasing fire resiliency in the long-term (Stephens et al. 2009).

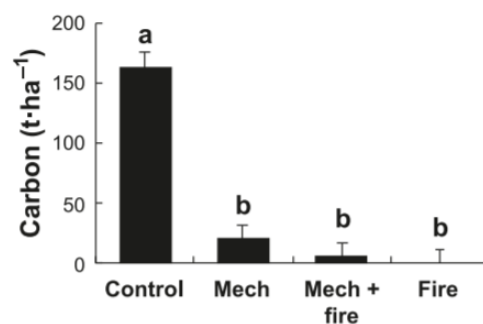


Figure 5: Mean live tree carbon with a greater than 75% chance of mortality during a severe wildfire. The mechanical treatment consisted of heavy thinning from below to maximize crown spacing on all trees greater than 25cm in diameter at breast height. The mechanical + fire treatment added a prescribed burn using a backing fire to the thinning treatment. From Stephens et al. (2009).

Concern has been raised over whether the carbon emissions associated with prescribed burns and thinning treatments justify their application to the landscape. In other words, are future emission reductions from lower intensity fires greater than current emissions from fuels treatments? Stephens et al. (2009) addressed this question by carefully inventorying the emissions associated with applying mechanical thinning, prescribed burns and a combination of thinning and burning treatments and comparing the results to the estimated amount of carbon that would be transferred from unstable to

stable pools by the treatments. The study defined a stable carbon pool as one where greater than 80% of the dominant and codominant tree species would survive a wildfire modeled under the 80th percentile of weather conditions (a high severity fire).

Emissions from all equipment used to thin the treatment plots including chainsaws, masticators, skidders, haul trucks and mill processing added up to an average of 1.2-1.5 t C per ha⁻¹. That amount was negligible compared to the emissions from prescribed burns. The emissions from the prescribed fire treatment averaged about 125 t C per ha⁻¹. In comparison, the amount of carbon that was shifted from unstable pools to stable pools was reduced by at least 140 t C per ha⁻¹ for all three treatments compared to the no action control as show in Figure 5 below. One unknown not addressed by Stephens et al. (2009) is the longevity of the effectiveness of the treatments. Treatments can remain effective anywhere from 5-20 years. If several reburns are needed to maintain the treatments efficacy, the net carbon benefit from the treatment decreases.

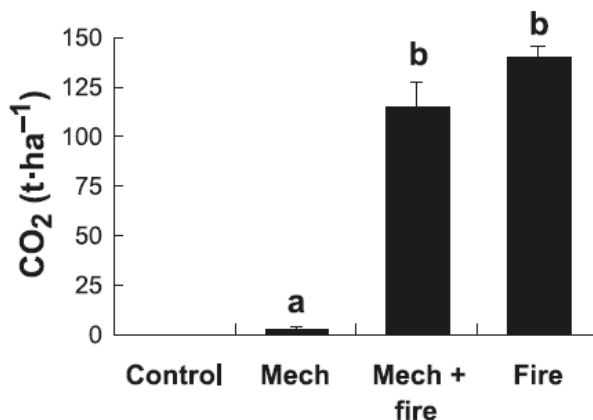


Figure 6: Average emissions per ha associated with various fuel reduction treatments. From Stephens et al. (2009).

A limitation of Stephens et al. (2009) is that resiliency to severe wildfires was modeled, not experimentally determined. In reality, a small 225 ha plot within a several hundred thousand or million ha forest would not be able to withstand the large, high severity fires that have been observed in the last several years. The treatment area would need to be at the landscape scale to achieve greater resiliency to today's mega fires, which is costly, time consuming and politically difficult to achieve as discussed in section six of this paper.

Other studies relying on direct measurements from test plots over a decadal timescale have also confirmed that thinning and prescribed burns are effective at reducing wildfire severity and ultimately stabilizing carbon pools in the Sierra Nevada (Wiechmann et al. 2015). Weichmann et al. (2015) completed a full factorial experiment involving three levels of thinning and two levels of burning to assess decadal changes in total carbon stocks and net sequestration of the 360ha study area. Treatments were applied to a mixed conifer forest at the 1300 ha Teakettle experimental forest in the central Sierra Nevada. The authors hypothesized that the carbon removal associated with the treatments would be re-sequestered by subsequent tree growth within the 10-year study period and that the proportion of carbon stored in large, stable, fire tolerant trees (e.g., pines) would increase.

There was no statistically significant difference between the pre and post treatment carbon distribution within fire tolerant and intolerant species (e.g., firs, incense cedars). However, the stand structure was altered. The treatments created more open patches of heterogeneous large diameter (>90cm) trees, which provides long-term carbon stability by fostering greater resilience to climate change and extreme fire (Wiechmann et al. 2015). Further evidence of the treatments' efficacy was demonstrated by the ratio between emissions from treatments compared to sequestered carbon. All treatments except the overstory thinning + prescribed fire treatment sequestered more carbon within the mean fire return interval (17 years for a Sierra Nevada mixed conifer forest) than was emitted or removed during the treatment. However, the control stands still had a greater carbon density than any of

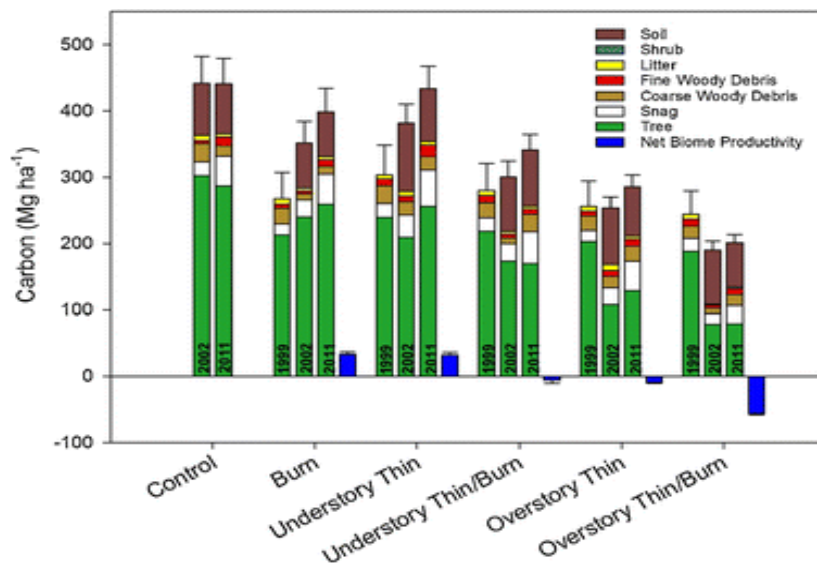


Figure 7: The different carbon stocks in Mg ha^{-1} of each carbon pool within the studies six treatment scenarios presented in Weichmann et al (2015). Treatments increased the proportion of carbon in the soil pool. Two treatments burn and understory thin had a positive net biome productivity, which was defined as the difference between the pre and post treatment carbon stocks minus the treatment related emissions. A positive NBP is similar to a positive NCEB over the study period. From Weichmann et al. (2015).

the treatment at the end of the 10-year study period as shown in Figure 7. This suggests that more time is needed for the large surviving trees to grow to return to pre-treatment carbon densities. Additionally, treatments may need to be reapplied more frequently as climate change creates more extreme wildfire

conditions. This may reduce the net carbon benefit of these treatments, but they are ultimately still effective at stabilizing more carbon in the long-term (Wiechmann et al. 2015).

4.1.2 Remote Sensing Modeling Simulations

Modeled simulations have examined how different thinning and prescribed burn treatments reduce tree density and reintroduce low-intensity surface fires to the ecosystem (Shuang Liang et al. 2018). The Landis II landscape model is a spatially explicit dataset that was used to model the impacts of treatments on carbon stocks and fluxes given different wildfire scenarios. It is important to note that all of the modeling simulations discussed in this section used the Landis II model and that most NCEB modeling relies on Landis II. While a powerful tool for modeling carbon dynamics, forest succession and other variables, the model is limited in its ability to integrate infinite scenarios at high resolution due to computer processing power. This means that simulations of large geographic areas like the entire Sierra Nevada must use lower resolution, which may treat dissimilar areas as equivalent, which introduces error into the analysis.

Shuang Liang et al. (2018) used the Landis II model to simulate thinning and prescribed fire treatments over 4,845,000 acres of Sierra Nevada forests under a distributed and an accelerated schedule from 2010 through 2100. The distributed schedule assumed a treatment pace of 581,400 acres per decade, while the accelerated schedule assumed 1,211,250 acres treated per decade, with all treatments being completed by mid-century. Currently, about 276,500 acres of USFS, BLM and non-federal forest lands receive some type of treatment each year throughout California (Forest Climate Action Team 2018). Given the current rate of treatments, the distributed and accelerated paces of treatments would require a doubling in treatment applications.

Treatments had a considerable effect on carbon dynamics and wildfire regimes, shifting the distribution of total area burned towards lower intensity, non-stand replacing fires as shown in Figure 8 below. Low severity fires have lower direct carbon emissions than high severity fires and also have lower emission in the long-term as fewer trees are killed and no landcover change occurs. The accelerated and distributed scenarios reduced cumulative wildfire emissions by 42% and 31%, respectively by 2100. Additionally, the timing of treatments impacted the eventual carbon stock. The accelerated schedule ultimately yielded 6 Tg C more than the distributed schedule by 2100 (Shuang Liang et al. 2018).

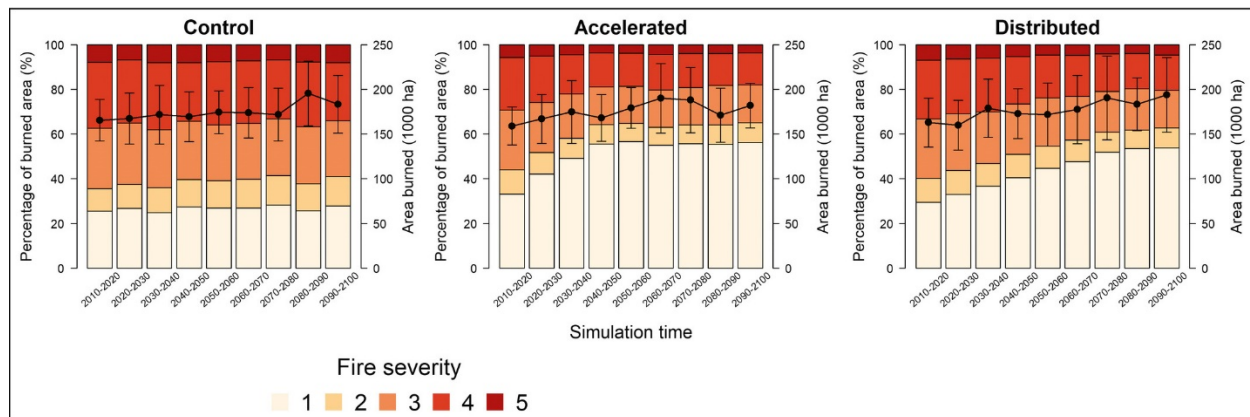


Figure 8: The change in area burned by low to high severity fire in the Sierra Nevada given two scenarios of thinning and prescribed fire treatments. The accelerated scenario treated 25% of the treatment area per decade while the distributed scenario treated 12%. A fire severity of 1 was a low severity surface fire whereas level 5 was defined as a stand-replacing fire. From Shuang Liang et al. (2018)

Another simulation completed using the Landis II landscape model of the Dinkey Creek watershed in Sierra National forest reinforced this finding. The study found that a thinning and maintenance burning treatment reduced mean fire severity by 25% under extreme wildfire conditions over the simulation period, but not under contemporary wildfire conditions as shown in Figure 9 below (Krofcheck et al. 2017) Contemporary wildfire weather conditions were defined as the average size of fires between 1984 and 2014, which may not reflect the wildfire conditions from 2014 to present. Because wildfire conditions are expected to become more extreme due to climate change in the coming decades, Krofcheck et al.'s findings should be applicable (Liang et al. 2017). The model was validated by comparing estimates of aboveground biomass with actual measurements from USFS Forest Inventory Analysis plots.

Thinning and prescribed fire treatments are effective in reducing fire severity and spread. A simulation of thinning and prescribed fire treatments on 86,000 ha of forest in the Lake Tahoe Basin using the Landis II landscape model demonstrated that the treatments changed species composition and stand structure and subsequently reduced fire risk in areas at high risk of severe wildfires. These effects can take decades to achieve but can ultimately “bend the carbon curve” to increase the NCEB of a forest over the long run (Loudermilk et al. 2017).

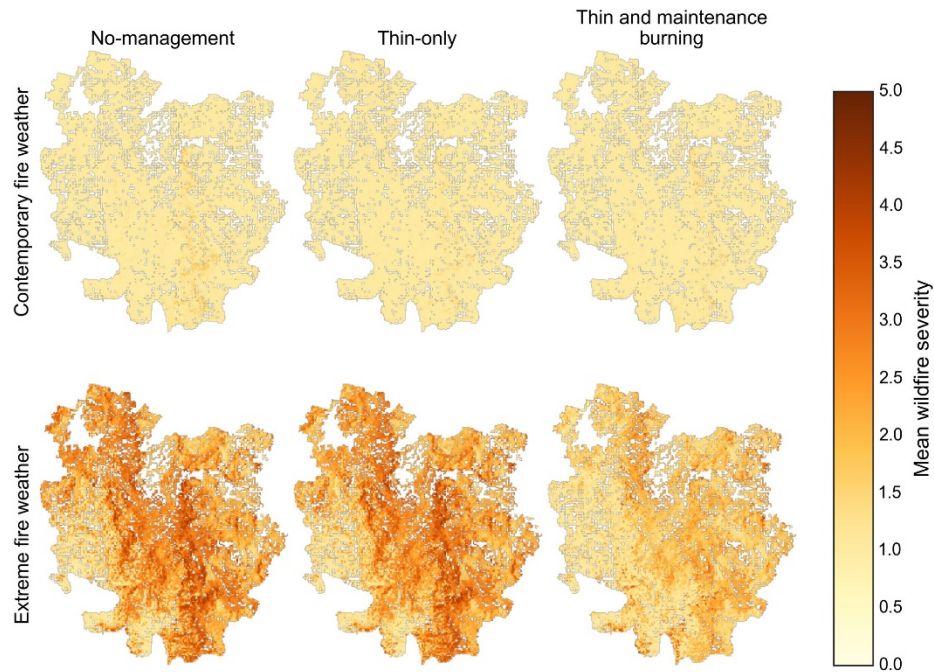


Figure 9: The mean wildfire severity decreasing following thin and maintenance burning treatments under extreme fire weather conditions. From Krofcheck et al. (2017a).

Hurteau (2017) also used the Landis II landscape model to demonstrate the efficacy of thinning and thinning + control burn treatments to moderate wildfire severity in a ponderosa pine forest in Northern Arizona. Ponderosa pine forests exist in many lower elevation bands of the Sierra Nevada and share a similar history of logging and fire suppression to ponderosa pine forests in Northern Arizona. The study had two treatment scenarios (thinning and thinning + control burn) and three timeframes (i.e. 2010-2019, 2050-2059, and 2090-2099) for a total of six scenarios.

Assuming a 1 in 50 probability of severe wildfire, the simulation concluded that 32.8–48.9% of the control area became carbon neutral or a net carbon source by the end of the century whereas >90% of the area treated with the thinning + controlled burn treatment remained a net carbon sink. The treatment efficacy was not impacted by warmer temperatures, reduced precipitation, and less ambient moisture, which are all expected because of climate change. The simulation also demonstrated that low severity fires had lower emissions than high severity fires covering the same area as show in Table 4 below (Hurteau 2017).

Table 4: Wildfire emissions by severity class

Severity Class	Mean Emissions (Mg C ha ⁻¹)	Standard Deviation
1–2	2.27	1.69
3	3.26	4.59
4	7.54	8.32
5	12.88	7.35

doi:10.1371/journal.pone.0169275.t001

Severity classes 1 and 2 represent surface fire and have the same parameterization. Severity class 3 includes some torching of mature trees. Severity class 4 includes some high severity patches. Severity class 5 is stand-replacing fire. From Hurteau (2017).

Overall, Hurteau (2017) found that treatments could not only maintain the Sierra Nevada as a carbon sink in the face of climate uncertainty and increasingly intense wildfires, but even sequester additional carbon by the end of the century. This additional sequestration was only possible after previous treatments had reduced the NCEB of the study area. However, it was advantageous to reduce NCEB in the early part of the century (2010–2019) to stabilize NCEB in the latter part of the century. Figure 10 displays this tradeoff.

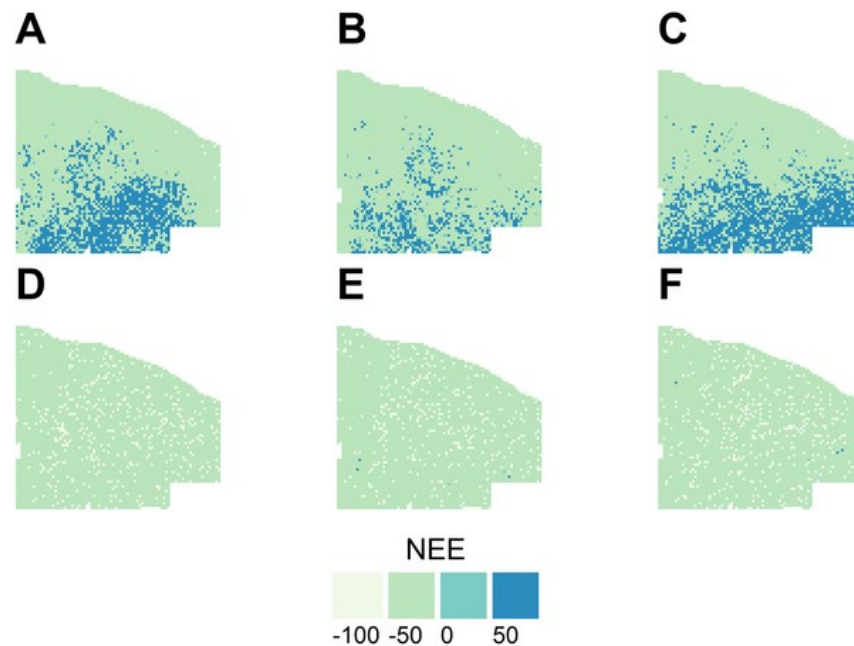


Figure 10: The net carbon ecosystem exchange in Mg C ha⁻¹ of a Ponderosa Pine forest in Northern Arizona. Net carbon ecosystem exchange is a metric similar to NCEB that expresses how much carbon is being emitted to the atmosphere. The numbers are a mean of values from 15 replicate simulations. Negative values indicate a carbon sink and positive values indicate a carbon source. (A), control 2050–59 climate (B), control 2090–99 climate (C), thin and burn 2010–19 climate (D), thin and burn 2050–59 climate (E), thin and burn 2090–99 climate (F) with the same wildfire parameterization over the 100-year simulation period. From Hurteau (2017).

Although an important component of total NCEB, fuel reduction treatments are not believed to affect soil carbon pools in the years immediately following a treatment (Dore et al. 2016; Boerner et al. 2008; Stephens et al. 2009). However, prescribed fire can reduce pools that feed the soil carbon pool such as vegetative litter and duff by 40% (Dore et al. 2016). Recent research attention on mountain meadow ecosystems in the Sierra Nevada as carbon sinks raises questions about whether meadows and soil carbon are a significant component of total ecosystem carbon. Montane meadows store more carbon per unit of area than surrounding forests and can either be a net carbon sink or source depending on climate and watershed characteristics (Reed et al. 2020). However, due to their small area relative to forests they are not a major carbon sink in the Sierra Nevada. Meadows that have been disturbed by grazing, recreation, road construction or other activities experience increased erosion, which alters the meadow's hydrology. Desiccated meadows are less productive than saturated meadows (Reed et al. 2020).

4.1.3 Drought and Bark Beetles

Between 2010 and 2017 over 129 million trees died in the Sierra Nevada from a combination of drought and bark beetle related mortality (Forest Climate Action Team 2018). From 2014 to 2017 an estimated average of 48.9% of trees in Eldorado, Sequoia, Sierra and Stanislaus National Forests died. Sierra National forest had the highest estimated mortality with around $58.7 \pm 3.7\%$ of trees dying in under 3 years. This mortality was documented with LIDAR and satellite imagery data as well as the USFS Aerial Detection Survey (Fettig et al. 2019). In 2016, approximately 52 MMT CO₂e was transferred from the live carbon pool to the dead pool as a result of drought stress and bark beetle mortality (Forest Climate Action Team 2018).

Thinning and prescribed fire treatments can create more drought resilient forests, which subsequently increases NCEB by reducing drought related tree mortality. A study simulating thinning treatments in Sierra Nevada mixed-conifer forests lead to more shade-intolerant fire-tolerant trees and greater carbon uptake as competition for soil, water and nutrients was reduced (Loudermilk et al. 2017). Reduced competitive stress on remaining trees increases a forests' ability to resist drought-related mortality (Young et al. 2017). Tree mortality throughout the Sierra Nevada increased by an order of magnitude during the extreme 2012-2016 drought (Fettig et al. 2019). Forests with higher stand density and homogeneity in species were more heavily impacted (Fettig et al. 2019). USFS scientists measured tree mortality in 255 different sized plots from 2015 to 2016 and found that mortality rate varied by species.

Overall, trees with larger diameters had an increased chance of survivorship though this trend was not always present depending on the tree species and the year assessed (Pile et al. 2018).

Van mantgem et al. (2016) used the extreme 2014-2016 drought to test whether areas in Yosemite, Sequoia and Kings Canyon National Parks treated with prescribed fires experienced less mortality than untreated areas. The study surveyed 9950 trees in 38 burned and 18 unburned mixed conifer forest plots at low elevation (<2100m). The burned plots had a lower stand density and had significantly less drought related mortality, suggesting that reduced competition for resources increased survivorship. With more frequent and intense droughts on the horizon as a result of climate change, prescribed fire and thinning can be used to mitigate additional tree mortality and carbon emissions from the Sierra Nevada.

Reduced competition for resources also results in increased tree radial growth and carbon sequestration (Loudermilk et al. 2017). Figure 11 shows a cross section of a pine tree to demonstrate how dramatically a treatment can increase radial growth. Sequestration can begin immediately after a treatment and this may offset emissions and decreases in NCEB that result from treatments (Wiechmann et al. 2015). Prioritizing survivorship of large fire tolerant, shade intolerant individual trees in thinning regimes can decrease the amount of time needed to re-sequester carbon removed or emitted during treatments.

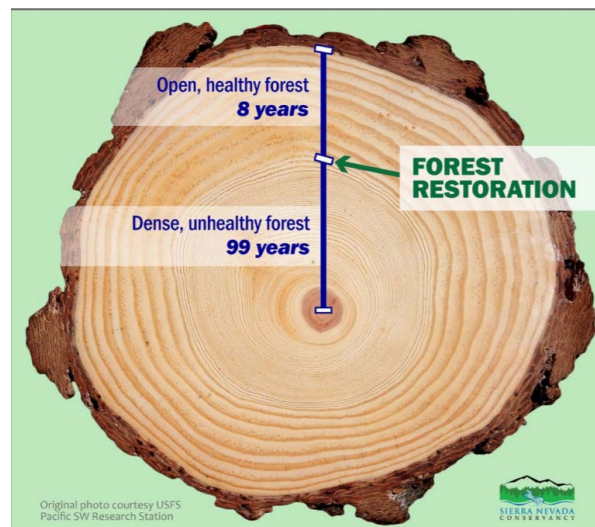


Figure 11: A cross section from a pine tree showing the difference in annual radial growth before and after a thinning treatment was applied on the landscape, which reduced competition and increased access to resources. From the Sierra Nevada Conservancy (2017).

In addition to drought, bark beetle infestations have decimated incomprehensibly large swaths of the Sierra Nevada, particularly in lower elevation forests and the Southern Sierra Nevada. Bark beetle

induced mortality strongly and negatively impacts NCEB because dead trees no longer photosynthesize and will eventually emit carbon during decomposition or combustion. Bark beetle mortality is strongly correlated with drought as desiccated trees stressed by drought are unable to secrete a canker resin that repels beetles (Kolb et al. 2016). In one simulation study from the Lake Tahoe Basin, carbon density was reduced by as much as 25% by climate driven bark beetle infestations after 2070 (Scheller et al. 2018).

Thinning and prescribed fire treatments increase resilience to bark beetle infestations through similar mechanisms as drought. Treatments reduce basal area, stand density and competition for resources, which increases resilience. Additionally, when trees are spaced farther apart it can make it more difficult for the bark beetles to communicate with each other to swarm and overwhelm an individual tree. A study of treated stands of sugar pine, ponderosa pine, incense cedar and white fir trees in Sierra and Eldorado National Forests found that prescribed fire treatments reduced the likelihood of beetle related mortality by 15% (Restaino et al. 2019). Current rates of treatment are insufficient to mitigate the largescale bark beetle mortality the Sierra Nevada is experiencing. Reintroducing low-severity surface fires at the landscape level and historic fire interval presents the best opportunity for mitigating future largescale bark beetle mortality (Restaino et al. 2019).

To maximize the efficacy of treatments, treatments should be performed in areas with the greatest risk of high severity wildfires (Foster et al. 2020; Loudermilk et al. 2017; Scheller et al. 2018). Treatments must be periodically reapplied to maintain their efficacy and each treatment has emissions associated with it. The more likely a wildfire is to coincide with the treatment, the greater the net carbon benefit because the emissions from the treatments are more likely to avert additional emissions in the future. In some cases, the treatment location is so important that the treatment only provides a net carbon benefit if performed in areas at high risk of a high severity burn (Krofcheck et al. 2017b). Areas at risk of high severity burns also most significantly lower long-term NCEB. High severity fires release large amounts of carbon and cause landcover conversion into low NCEB ecosystems, meaning that treatments that reduce the intensity and spread of fire help maintain a positive NCEB over the long-term.

A breadth of literature validates the efficacy of prescribed burning, thinning and reforestation treatments in maintaining the Sierra Nevada as net carbon sink over the long-term. Studies have examined how these treatments impact fire regimes, resilience to drought and bark beetle mortality,

landcover change and carbon biogeochemical cycling. Treatments can reduce the intensity and spread of extreme wildfires while reintroducing beneficial low-severity fires to the landscape. Treatments help alter the species composition, stand density and age of these forests, all of which increase resilience to the two largest drivers of tree mortality in the Sierra Nevada over the last decade: bark beetles and drought. Studies across a variety of Sierra Nevada forests carried out over decades using direct measurement and remote sensing modeling simulation methodologies verify these results. Variables that influence treatment effectiveness include the type, location, timing, and duration of treatments as well as the probability and severity of wildfire. Studies examining the impact of treatments on mitigating drought and bark beetle mortality further bolster these findings. A scientific consensus exists that these treatments can help manage the Sierra Nevada as a carbon sink, though the extent of the efficacy is under debate.

4.2 Evidence that forest management treatments are not effective at maintaining a positive NCEB in the Sierra Nevada

Disagreement over the efficacy of thinning, prescribed fire and reforestation treatments for maintaining a positive long-term NCEB in the Sierra Nevada exists in the literature. Measuring the impacts of treatments on carbon dynamics at the landscape scale is complicated and differences in carbon measurement, methodology, length of study and study location can impact the results. Overall, most studies conclude that treatments have some positive impact on increasing carbon stability and reducing risk of extreme wildfire, but several studies highlight the important limitations and contingencies of these treatments. Out of the 18 studies reviewed for this project, only three concluded that treatments were not effective at maintaining carbon stability over the long-term. This is similar to the finding of a systematic literature review of treatment effects on North American forests, which found that 64 of 73 studies concluded that treatments were effective at preserving ecosystem carbon.

For example, reforestation treatments have been found to underperform no treatment controls in terms of carbon sequestration and NCEB. Powers et al. (2013) studied the effect of post-fire treatments such as salvaging, logging and planting new trees on carbon storage in mixed conifer Sierra Nevada forests using 300ha test plots in Plumas and Lassen National forests. Forests where the tree canopy survived outperformed all treatment types. No salvage plots outperformed salvaged and intensively managed plots in terms of carbon stocks 10 years after a fire. Surprisingly, among severely burned areas the non-managed plots had the highest amount of total carbon remaining. However, the study also

included in its carbon inventory the proportion of carbon in pools likely to increase fire severity (i.e. fine fuels, duff, understory fuels) vs. carbon in more fire-resistant pools (i.e. snags, coarse woody debris). This shows that although the total amount of carbon stored in non-managed plots was higher, it was also more unstable and likely to reburn in a high severity fire (Powers et al. 2013).

Others dispute the NCEB benefits of treatments because of unrealistic assumptions around wildfire probability and the difference in carbon emissions between low-severity and high severity fires. (Campbell, John L. et al. 2012). For example, Campbell et al. (2007) estimates that low-severity fire emissions are 70% of high-severity fire emissions. This is because 71% of emissions from both fires come from surface fuels such as litter, duff and downed wood which are burned ubiquitously by low-severity surface fires (Campbell, John et al. 2007). Others, including Hurtreau and North (2009) disagree with this number, claiming the emissions can be as low as 40% of high-severity fire emissions. Campbell et al.'s (2012) research suggested a 1% probability that any specific area in the Sierra Nevada is burned by a wildfire in a given year. Another study, (Baker, 2008) suggested that 3% of a treatment area would burn over the 20-year effective lifespan of that treatment. Wildfire regimes-including frequency and severity- is rapidly changing in the Sierra Nevada due to climate change. In the last 10 years since Campbell's study was published, nine of the ten largest fires in California history have occurred. These fires almost certainly change the probability of wildfire. Several studies have confirmed that this trend is expected to increase towards mid-century as extreme fires are exacerbated by climate change (Liang et al. 2017).

Foster et al. (2020) used the same experimental plots as Stephens et al. (2009) over a 14-year period to measure the impact of the same treatments but came to a different conclusion about the overall efficacy of the treatments. The same experimental plots are often used in carbon biogeochemical cycling research because the USFS and the University of California manage these plots out of established field research stations throughout the state. This provides easy access to and logistical support for study areas, which greatly reduces the cost of doing research.

Foster et al. (2020) measured the impact of treatments on carbon stocks, carbon stability, expected live tree carbon and expected total aboveground carbon and expected live tree carbon. The overall research question was the same as Stephens et al. (2009): to determine whether the treatments provided a net benefit to long-term NCEB. The study did not account for emissions associated with running equipment

for mechanical thinning, prescribed burns or soil carbon. As expected, the mechanical thinning, prescribed burn and combined thinning and burning treatments all decreased carbon stocks relative to the control, demonstrating the short-term carbon costs of these treatments. Stable live tree carbon was defined as the carbon in trees expected to survive three years after a severe wildfire. The treatments were all highly effective at increasing the amount of stable live tree carbon in their plots as shown below in Figure 12, which is consistent with (Stephens et al. 2009)

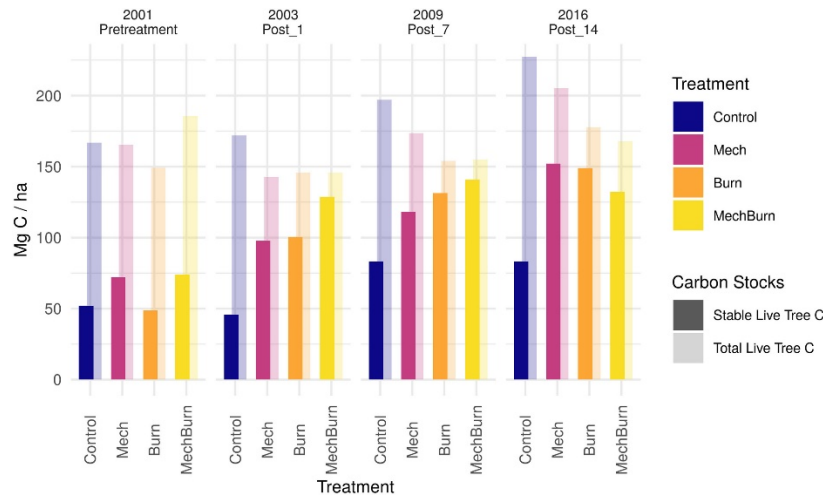


Figure 12: Stable live tree carbon and total live tree carbon measured post treatment at an experimental research forest in the Sierra Nevada. Although the amount of total carbon measured in Mg C per ha was lower for the three treatments than the control, the amount of stable carbon that would survive a severe fire was substantially higher, especially at the end of the 14 year study period. From Foster et al. (2020).

Differences began to appear between Foster et al. (2020) and Stephens et al. (2009) when the treatment's impact on expected live tree carbon was examined. Expected live tree carbon was defined as the mean of live tree carbon and stable live tree carbon, weighted for wildfire probability. Expected total aboveground carbon was the average of total aboveground carbon pre and post fire weighted for wildfire probability. Together expected live tree carbon and expected total aboveground carbon were the best proxies for net carbon benefits for NCEB. While Foster et al. (2020) and Stephens et al. (2009) agreed that the treatments increased the size of the stable live tree carbon pool, when wildfire probability was incorporated to calculate expected live tree and expected aboveground carbon, the studies diverged.

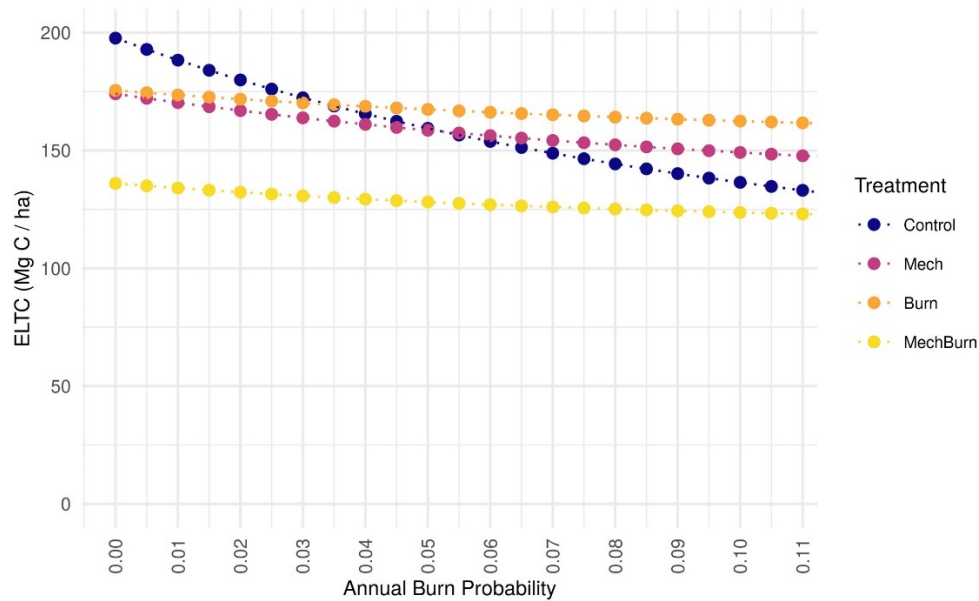


Figure 13: Expected live tree carbon measured post treatment at an experimental research forest in the Sierra Nevada. Expected live tree carbon is the mean of live tree carbon and stable live tree carbon, weighted for wildfire probability. This figure demonstrates that wildfire probability moderates the NCEB benefit of various treatments. From Foster et al. (2020).

A key conclusion of the study was that the probability of high severity wildfire moderated the net carbon benefits of all three treatments. In lower wildfire probability scenarios, the control had a higher expected total aboveground carbon than any of the treatments. However, under high wildfire probability scenarios, the thinning and the prescribed burn treatments outperformed the control in terms of expected live tree carbon. For expected total aboveground carbon, only under assumptions that the high severity fire was almost certain to occur and that the majority of carbon in killed trees would be emitted to the atmosphere, were the prescribed burn and mechanical thinning + prescribed burning treatments competitive with the control.

Overall, these findings differ from Stephens et al. (2009), which found that all the treatments increased the long-term NCEB of the study area under all conditions. This demonstrates that the assumptions underpinning each study, such as wildfire probability, climatic conditions, drought, and other exogenous variables impact the overall results. The differences can primarily be explained by the differences in assumptions around wildfire probability and the length of the study. Stephens et al. (2009) determined the likelihood that a given test plot would burn any time in the next hundred years was high, whereas Foster et al. (2020) assumed probabilities ranging from .01 to .11. Foster et al. (2020) modeled carbon dynamics for 14 years after treatment application but does not account for the long-term implications of landscape cover change from forests that do not regenerate after a high-severity fire. This means that

while the carbon costs of treatments may outweigh the benefits in the short-term, they may not in the long-term. Foster et al. (2020) concluded by noting that NCEB is not the sole forest management goal and these treatments provide many other important co-benefits, which will be further explored in section V of this paper.

These limitations do not hinder the overarching conclusion that prescribed burn, thinning and reforestation treatments can help maintain the Sierra Nevada as a net carbon sink over the long-term. All but three of the studies reviewed concluded that the treatments were effective. Studies that found that treatments were not effective arrived at this conclusion because they determined the probability of a wildfire overlapping with a treatment area during the period in which the treatment was still effective to be low. Prioritizing treatments in areas with high ignition potential can help mitigate this effect. Additionally, climate change is dramatically increasing wildfire probabilities, even in just the last five years. There are many variables including the type, timing, scale, probability of wildfire and frequency of treatments that determine the overall efficacy. Treatments often have overlapping benefits of increasing resilience to drought and bark beetle infestations while increasing long-term carbon stability. Additional co-benefits of treatments include protection of life and property from wildfires, improved air and water quality, additional jobs and economic redevelopment and recreational opportunities and will be discussed in section V.

4.3 Limitations of modeling impacts of forest management treatments on NCEB

Accurately modeling the impact of thinning, prescribed fire, and reforestation treatments on NCEB over the next century or even a few decades is challenging. The studies and models used to generate these estimates have many important limitations discussed in this section. Most studies, including all studies relying on the Landis II model, neglect the soil carbon pool, which stores a significant amount of total ecosystem carbon. While several studies documented that treatments have no impact on the soil carbon pool immediately following the treatments, little research exists on potential impacts over the long-term. Estimates of the proportion of soil carbon compared to total ecosystem carbon vary depending on the type of forest and the study, but a consensus exists that it is at least 20% (Powers et al. 2013) (Stewart et al. 2011). By omitting carbon flux estimates of this pool, NCEB estimates introduce a large potential source of error.

Studies that rely on direct measurements from test plots are severely limited by their scale and duration. Most forest plots treated with thinning or prescribed burn treatments are only a few hundred ha at their largest due to the high cost of larger studies. Extrapolating the results of small pilot scale studies to large landscapes can be problematic because the fire dynamics of large megafires are very different. Treating a few dozen or even hundred ha in targeted areas may be beneficial to protecting assets such as homes or buildings but is unlikely to reduce overall fire severity or post fire carbon dynamics in any meaningful way at a landscape scale (Foster et al. 2020). The longest direct measurement studies were about 15 years long due to funding and logistical constraints, but succession and reforestation are biological processes that occur over decades. The short duration of direct measurement studies may therefore miss the long-term effects of the treatments on NCEB.

In comparison, simulations are useful in modeling treatment effects on NCEB because they can be completed at more meaningful scales and time horizons at a fraction of the cost. However, the stochastic nature of wildfire makes it inherently difficult to model. The further into the future models estimate, the more uncertain the results. As previously discussed, the probability of wildfire is key to determining the effectiveness of treatments, and it is difficult to predict future wildfire probability. Forest regeneration is also complex and landscape cover changes are not included in some of the simulations discussed in section 3.1. Landscape cover change is a grave concern for the Sierra Nevada as drought and wildfires are anticipated to convert large parts of coniferous forest to dry scrublands where only small, water-hardy tree species survive (Kitzberger et al. 2016).

While some authors e.g., Campbell et al. (2012), Foster et al. (2020), Powers et al. (2013) have noted the limitations of these treatments, a consensus that more treatments are needed on the landscape to further a variety of land management goals including water supply, air quality, carbon stability, sustainable timber harvest and recreation exists. When these co-benefits are considered, the case for implementation of treatments at the landscape scale is obvious. The current pace and scale of treatments is inadequate to ensure that the significant amount of carbon currently stored in the Sierra Nevada remains there over the long-term.

V. Cobenefits of thinning, prescribed burning and reforestation treatments

Aside from maximizing carbon stability and fighting climate change, thinning, prescribed burning and reforestation treatments also provide a number of important co-benefits that should be considered

when evaluating whether to invest in increasing the number and scale of treatments on the landscape. While the carbon benefits are sufficiently significant to warrant being pursued in their own right, when the cobenefits of protection of life and property, improved air and water quality, jobs and economic opportunity and intrinsic value are factored in, it becomes clear that these treatments yield dividends far beyond their initial investment. A more precise understanding of the monetary benefits of these co-benefits would improve cost benefit analyses of treatments and may help identify new funding mechanisms for implementing treatments. This section describes the co-benefits of thinning, prescribed burning and reforestation treatments and presents some general estimates and examples of their monetary value relative to the cost of treatments.

5.1 Reduction of catastrophic wildfires can save lives and avert billions in property damages

California wildfires in the last five years have been the most destructive in history in terms of both property damage and human lives lost. Seven of the top 10 wildfires with the greatest number of destroyed structures have occurred since 2015 (Cal Fire 2021). Property damage costs from wildfires have grown substantially in the last five years, with 2020 fires destroying over 10,000 structures and inflicting over \$12 billion in property damages (Roman et al. 2020). Fire suppression costs have grown in tandem, with Cal Fire spending over a billion dollars in emergency funds in 2020 to fight fires in addition to a \$2.5 billion annual operating budget.

Proposed solutions to mitigating this extensive death and destruction are numerous and complex but a clear consensus exists that thinning and prescribed burning treatments are an important component. A wealth of literature has demonstrated that treatments can reduce wildfire risk in key areas within the wildland urban interface (Moghaddas and Craggs 2007; Murphy et al. 2010; Safford et al. 2009). Treatments provide invaluable fuel breaks that firefighting crews can exploit to build containment lines and stop the fire from reaching adjacent assets. Treatments alter fire behavior and make it less intense, providing valuable time for firefighters to coordinate additional resources and slow the fire.

Several case studies demonstrate that treatments can help save Sierra Nevada communities from devastating wildfires. In Trinity County, a partnership between the USFS and the local community of Weaverville established a 13,000-acre community forest where community partners could fund and implement treatments on the landscape. Sale of small diameter timber from the forest was used to fund a thinning and prescribed burn treatment in an area known as Five Cent Gulch, just above the town of

Weaverville. When a nearby wildfire ignited and intersected with the treatment area firefighters reported that the fire slowed down, enabling firefighters to control the blaze (Peterson 2019). In Silverthorne Colorado, 300-500 ft. wide fuel breaks cut into bark beetle impacted lodgepole pines were credited with saving over 1400 homes and averting nearly a billion dollars in property damage (Krake 2018).

Another example of treatments successfully averting significant property damage is the 2017 Milli Fire near Sisters, Oregon within Deschutes National Forest. Deschutes NF is a mixed conifer forest, that is similar to many Sierra Nevada forests. The Deschutes Collaborative Forest Project generated public support and funding for thinning and prescribed burn treatments in critical areas adjacent to vulnerable structures. The treatments provided a fuel break that reduced fire spread and allowed for better aerial drops of water and flame retardant to suppress a subsequent wildfire that burned through the treatment area (Deschutes Forest Collaborative Project 2021).

Unfortunately, no systematic estimate of the total amount of property damage that has been averted due to fuel treatment applications exists. However, the number of wildfire damaged structures has steadily climbed over the past ten years and is anticipated to increase even more in the future (Safford et al. 2009). With increased wildfire likelihood and severity, fuel treatments will yield a greater return on investment because they are more likely to intersect with wildfires. One relatively small fuel treatment of a couple hundred acres can have a large impact on protecting lives and property, even if it is too small to affect carbon biogeochemical cycling at the landscape scale (Moghaddas and Craggs 2007).

5.2 Improved air quality

Air quality impacts from recent wildfires have been unprecedented. In 2020, smoke plumes from California wildfires stretched across the entire United States to the Atlantic Ocean and blotched out the sun for weeks at a time in populated areas such as the Bay Area and Sacramento. Air quality levels in the Bay Area remained hazardous for weeks, disrupting daily outdoor activities. Wildfire smoke contains many harmful contaminants including PM_{2.5}, volatile organic compounds, and nitrous oxide and is associated with adverse health impacts such as asthma, chronic obstructive pulmonary disease, respiratory distress, and cardiovascular disease (Reid, Colleen et al. 2016).

Low-income and minority communities are more vulnerable to negative wildfire smoke impacts because they are disproportionately burdened by preexisting health conditions, have low adaptive capacity, and are more likely to have jobs that require them to be outside. Lack of access to air conditioning, air filters, and quality healthcare are examples of low adaptive capacity. This increased vulnerability translates into tangible health impacts such as increased risk of cardiac arrest hospitalizations for low-income residents compared to higher socioeconomic status residents as shown in Figure 14 below (Jones et al. 2020). Other studies have also found that income was a moderating variable for respiratory and cardiovascular hospitalizations and emergency department visits during wildfire smoke events even after preexisting conditions were controlled for (Reid, Colleen E. et al. 2016).

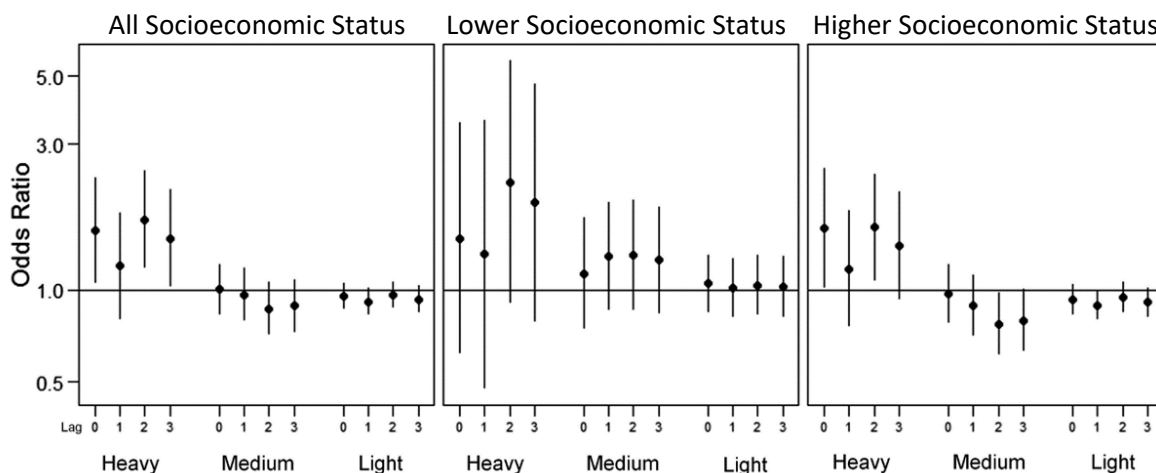


Figure 14: The difference in likelihood of being hospitalized for cardiac arrest among 14 California counties. Smoke density is shown on the x axis and the likelihood of hospitalization is shown on the y axis as an odds ratio. An odds ratio is a measure of association that described the relationship between an exposure and a health outcome among two different groups. An odds ratio greater than one indicates that the exposure might be a risk factor for the disease, whereas a ratio at or below one indicates the exposure and outcome are not related. High socioeconomic and low socioeconomic communities exposed to the same wildfire smoke events had different rates of respiratory and cardiac hospitalizations. Lower socioeconomic status was defined as a zip code with over 40% of the population living below the poverty line. From Jones et al. (2020)

A total of 3,652 deaths were attributed to air pollution from wildfire smoke in California in 2018. Cost estimates for mortality, work time lost, and direct medical expenses totaled \$32.2 billion (Wang et al. 2020). Mortality dominated the total as each statistical life was valued at \$9 million (Wang et al. 2020). Increases in asthma attacks, strokes and cardiovascular impacts as a result of increased wildfire smoke were not limited to California. Smoke traveled as far as Vancouver, Canada. Within a few hours of the smoke hitting Vancouver, ambulance calls for respiratory and cardiovascular emergencies jumped 10% (Wang et al. 2020). Similar results have been replicated nationally, with one study of wildfire smoke impacts on respiratory and cardiovascular hospital admissions for Medicare enrollees concluding that

respiratory hospital admissions rose 7.2% during “smoke wave” events. Wildfire smoke waves were defined as two or more consecutive days with $PM_{2.5}$ concentrations $> 37\mu g/m^3$ from wildfire smoke (Liu et al. 2017).

Prescribed burns can also generate unhealthy levels of wildfire smoke that exceed U.S EPA’s National Ambient Air Quality Standards. However, prescribed burns are regulated as an emission source under the Clean Air Act and must be approved by local air quality management districts in California. Fire managers or Burn Bosses must often choose favorable atmospheric conditions for optimal smoke dispersal to alleviate smoke impacts to communities. Advanced notice and public awareness campaigns can help communities prepare for smoke from prescribed burns by purchasing masks and indoor air filters. Local governments can setup clean air shelters at community centers, libraries, and other public places to help protect vulnerable low-income populations and sensitive individuals. Overall, emissions from the same area burned by prescribed burns are lower than emissions from the large catastrophic wildfires that have dominated the Sierra Nevada for the last five years (Wiedinmyer and Hurteau 2010).

5.3 Increased water availability and quality

The Sierra Nevada is an important source of drinking water for over 23 million Californians across the entire state (Podolak et al. 2015). Thinning and prescribed fire treatments can help increase the quantity and quality of water available to downstream users for irrigation, hydroelectricity, and residential use (Boisramé et al. 2019). Conversely, high-severity wildfires can severely impair water resources as erosion, ash, debris, and nutrient loading threaten watersheds after major burns. High-severity fires are more damaging to water resources than low-severity prescribed burns because there is a greater risk of erosion when no trees or vegetation remain. These impacts can be very costly for water utility providers. Water utilities may have to modify their treatment methods, undertake slope stability projects, and replace infrastructure. Ash and debris can clog treatment systems, causing costly damage. The 2013 Rim Fire in Stanislaus National Forest, just outside of Yosemite National Park, cost the San Francisco Public Utilities Commission an estimated \$55 million in direct damages. A total estimate of \$100 million to \$736 million of indirect damages to ecosystem services from the Rim fire was also assessed and included recreation and tourism, air quality, pollinator protection, carbon sequestration, soil formation, water retention and more (Batker et al. 2013).

Treatments increase water storage capacity, streamflow and snowpack retention by altering the timing of water release and reducing evapotranspiration. Treatments reduce vegetative cover which in turn reduces evapotranspiration and increases the fraction of precipitation that is diverted to runoff (Bales et al. 2011). Additionally, the Sierra snowpack helps retain water later into spring where it can be stored for use during the dry summer months. Thinning treatments can increase snowpack retention as a reduction in stand density leads to more snow falling to the ground than in the canopy, where it would evaporate. The Sierra Nevada Watershed Enhancement Environmental Project found that sustained and extensive treatments on experimental test plots in Sierra Nevada mixed conifer forests increased water yield by as much as 16% (Bales et al. 2011).

Research from the 150-km² Illilouette Creek Basin in Yosemite National Park has also demonstrated that treatments can increase water yields. Researchers compared annual streamflow, subsurface water storage capacity and evapotranspiration in the basin under a fire suppression management policy that existed until 1972 and a managed fire policy that reintroduced fire to the landscape from 1972 to present (Boisramé et al. 2019). A 25% reduction in canopy cover in the basin occurred between 1972 and 2017 as a result of the policy change, with a fire burning the basin every 7 years on average. Data from stream flow gauges were compared in the pre and post treatment periods. After controlling for interannual variation, Boisrame et al. (2019) concluded that the treatments resulted a 5% increase in mean annual outflow for the basin, which amounts to $7 \times 10^6 \text{ m}^3$ or 1/60 the capacity of the nearby Hetch-Hetchy Reservoir each year (Boisramé et al. 2019).

Prescribed burn and thinning treatments can also positively impact water quality. Overly dense coniferous forests can become sources of N, P and C nutrient loading into sensitive waterbodies. Routine burning reduces nutrient accumulation on the forest floor and can improve water quality. A study of watersheds surrounding Lake Tahoe demonstrated this effect by comparing nutrient loading from treated and untreated watersheds (Miller et al. 2010). Miller et al. (2010) found that N and P inputs in litter across three ecosystem types (e.g., chaparral, mixed conifer forest and Jeffrey pine forest) were substantially higher in the untreated watershed compared to the treated watershed and that additional nutrients were mobilized by runoff into Lake Tahoe. Table 5 below shows the simulated increases in nutrient loading in kg per ha and percentage of watersheds under fire suppressed and historical fire regimes (Miller et al. 2010). By reintroducing fire to the ecosystem and returning to a fire regime more closely associated to the historical norm, nutrient loading to Lake Tahoe could be reduced.

Table 5: Simulated litter N and P for different ecosystems under two different fire regimes.
N and P nutrient content in litter in kg ha⁻¹ under historical and suppression fire regimes in the Lake Tahoe Basin. From Miller et al. (2010).

		Litter N kg ha ⁻¹	% Incr.	Litter P kg ha ⁻¹	% Incr.
Jeffrey pine	Historical Fire	272.96 ± 6.83	106.8	18.95 ± 0.46	135.51
	Fire Suppression	564.41 ± 11.04		44.54 ± 1.04	
Mixed conifer	Historical Fire	102.09 ± 5.83	42.6	6.23 ± 0.39	43.9
	Fire Suppression	145.60 ± 8.42		8.96 ± 0.58	
Chaparral	Historical Fire	10.01 ± 0.66	187.6	0.97 ± 0.14	74.9
	Fire Suppression	28.79 ± 0.49		1.69 ± 0.13	

Monetizing this valuable co-benefit is an appealing funding mechanism for future treatments. Unlike air quality, impacts to water quantity are divisible and can be privatized by water utilities. A cost benefit analysis comparing the monetary value of increased average annual streamflow and water supply in 11 Northern California watersheds to the costs of implementing thinning treatments in the same watersheds concluded that sale of the increased water yield could cover between one third to the full cost of the treatment depending on whether the treatments yielded a low or high estimate increase in streamflow (Podolak et al. 2015). Podolak et al. (2015) concluded that if thinning treatments were tripled in the Feather River watershed, the watershed with the greatest area available for thinning, a 6% increase in average annual streamflow would yield an additional 97,000 to 285,000 acre feet of runoff that could be used for irrigation or municipal use after generating hydroelectricity. Water demand and prices are greater during the summer than the winter, so moderating the timing of stream flows can be just as valuable as increasing stream flows. Similarly, runoff at high elevations in the Sierra can pass through a series of several hydroelectric dams generating as much as \$36 per acre foot of water (Bales et al. 2011). Treatments have the potential to quantifiably improve water quality and availability to millions of California residents, providing a valuable co-benefit that can be monetized and may even provide a potential sustainable funding mechanism for additional treatments.

5.4 Jobs and economic opportunity for underserved communities

Implementing treatments on the landscape level will require tens of thousands of white collar and blue-collar professionals including scientists, engineers, environmental managers, firefighters, loggers, equipment operators, lumber mill workers and construction workers. Public investment in dramatically expanding the scale of treatments can spur employment and professional development opportunities for economically depressed and underserved communities. A Climate Conservation Corps modeled after the original 1930's New Deal era Civilian Conservation Corps could provide job training programs focused on developing marketable skills that could be applied outside of the forestry industry.

Several examples of successful state and local programs operating with this model exist, including Oakland's Civicorps, the California Conservation Corps, and the California Conservation Camp network. Oakland's Civicorps assists young people 18-26 facing serious life adversity such as, unplanned pregnancy, homelessness, foster care and involvement with the criminal justice system with obtaining their high school diploma and then securing employment or college admission. Civicorps completes different environmental projects including recycling, e-waste collection, trail work, wildfire thinning treatments, habitat restoration, and trash removal from waterways. Seventy-four percent of students earn their high school diploma, one of the highest rates in Oakland and 85% of students are either employed or enrolled in a four-year degree program after graduation. In 2018, the program had a \$8.2 million operating budget and employed 262 corps members that applied treatments to 483 acres, cleared 42 miles of waterways, repaired 36 miles of trails, and collected 2,327 tons of recyclable materials.

The California Conservation Corps was created in 1976 and employs 3,000 young adults each year to implement various conservation and natural resource projects throughout California. In 2020, corps members assisted fire crews and worked on watershed protection and hillside stabilization projects to protect water resources in Sierra National Forest after the Creek Fire. Forest restoration work has the potential to provide stable, dignified employment with a clear sense of purpose to people in underserved communities. A climate conservation corps could lift people up from the challenges the pandemic has brought by providing public service jobs with a living wage and basic benefits.

The California Conservation Camp is a joint program between the California Department of Corrections and Cal Fire to use State Prison inmates serving sentences for non-violent offenses for a variety of firefighting and natural resources work. Nearly 4,300 inmates live and work at 39 camps throughout the

state and collectively spend 3 million hours responding to fires each year. The typical operating cost for each camp is \$2.5 million, which includes payroll and operating costs. For comparison, Cal Fire employs around 6,200 firefighters, so inmate firefighters are around 40% of California's state firefighting force.

Aside from public sector employment, an investment in increasing treatments in the Sierra Nevada will have a multiplier effect in economically depressed rural communities adjacent to forests that boosts private sector employment. The Deschutes National Forest Collaborative Project estimates that its forest restoration projects have resulted in the creation of 4,161 local jobs in diverse fields ranging from trucking to hydrology over the last 10 years (Deschutes Forest Collaborative Project 2021). Nearby hotels, restaurants, grocery stores and small businesses will benefit tremendously from the increase in workers implementing treatments in the Sierra Nevada providing jobs that cannot be outsourced.

As the logging and mining industries have waned over the last few decades throughout the Sierra Nevada, recreation and tourism have boomed. In 2019, tourism in the Sierra Nevada generated \$3.6 billion in taxable sales and supported 36,400 tourism jobs. The nine National Forests in the Sierra Nevada received 22.8 million visits and Yosemite National Park alone attracted more than 4 million visitors, with international tourists listing it as the most important attraction to see in the state (Wilson et al. 2020).

Several studies have documented the significant harm wildfires have already inflicted on the tourism and recreation industry in the Sierra Nevada. The 2013 Rim Fire resulted in a loss of \$211 million in recreation and tourism business (Batker et al. 2013). The 2018 Ferguson Fire outside of Yosemite cost Mariposa County, a gateway community to the park, \$46 million in lost travel revenue and over \$1 million in lost tax revenue, amounting to about 12% of the county's total budget (Wilson et al. 2020). Because the large megafires of the past 10 years can last for months, the economic impacts can be both long-term and devastating for gateway communities in the Sierra Nevada. A survey of California residents and non-resident visitors to the Sierra Nevada since 2014 showed that 90% were less likely to visit the region due to impacts from wildfires. Additional commentary from interviewees revealed how the perception of a degraded environment reduced the likelihood of actual visits (Wilson et al. 2020). Treatments can protect the long-term sustainability of this vital industry by reducing wildfire severity, evacuations, smoke impacts and improving visitor safety. Additionally, these same treatments can put tens of thousands of unemployed workers back to work and act as a stimulus for underserved rural communities in the Sierra Nevada.

5.5 Total Value of cobenefits in 2018

The combined value of these cobenefits in the Sierra Nevada in 2018 was conservatively estimated at \$61.551 billion as shown in Table 6 below. A \$1 million value of a statical life was added to the \$27.7 billion in property damages to calculate the total cobenefit or protection of life and property. Healthcare costs were calculated by totaling wildfire smoke related hospital emergency department and clinician visits, and prescription medicine costs. Water quantity benefits were derived from Podolak et al. (2015) while water quality costs were taken from public facing websites for the San Francisco Public Utility Commission and the Placer County Water Agency for the 2013 Rim Fire and 2014 King Fire. There are many other water utilities that have not reported how much wildfires have cost them. Air quality benefits are directly from Wang et. al (2020).

Admittedly, there is no guarantee that all these damages could have been avoided with the application of treatments on the landscape. It is unlikely that treatments would have averted all property damage costs but saving even a fraction of the homes would be significant. Some of the estimates, such as the air quality healthcare estimate and property damage estimate include costs incurred by fires outside of the Sierra Nevada region. Other estimates are undercounting total cobenefits. Wages for only 69 workers working on one project were included for the “wages of workers implementing treatments” category. Many other tourist destinations besides Yosemite suffered greatly from wildfire caused closures and cancellations, but do not have published economic analyses detailing tourism industry losses. Regardless, the value of the cobenefits dwarf the roughly \$300 million per year estimated to be needed to implement treatment at a pace and scale sufficient to restore Sierra Nevada forests to a healthier and more resilient state.

Table 6: Total Value of Co-benefits of treatments in 2018

Cobenefit	Estimated Value in 2018	Notes/Source
Protection of life and property	\$27.90 billion	Ninety people died in Sierra Nevada wildfires in 2018. The value of a statistical life is \$1 million. \$27.7 billion in insurance losses from property damages were recorded throughout all of California from all wildfires. Around \$14 billion was from the Camp Fire alone. (Wang et al. 2020)
Improved air quality	\$32.2 billion	Wang et al. (2020)
Increased water availability	\$71.73 million	Podolak et al. (2015) estimated the potential increase in water yield in acre feet per year as a result of thinning treatments in 11 Sierra Nevada watersheds in table two. Under a high yield scenario, a total of 505,138 acre feet per year (AFY) could be expected from all the watersheds. Values of \$36 per AFY for hydroelectricity generation and \$106 (average of summer and winter water prices) per AFY for the water supply were used.
Improved water quality	\$65 million	Wildfires impact water quality and result in direct costs to water utilities. The San Francisco Public Utilities Commission estimated damages from the Rim Fire cost them \$55 million infrastructure replacement and increased treatment costs. The Placer County Water Agency estimated it spent \$10 million on treatment and stabilization projects after the King Fire in 2014.
Tourism industry impacts	\$211 million	The cost of the closure of Yosemite National Park due to the 2018 Ferguson Fire was included (Wilson et al. 2020).
Wages for workers implementing treatments	\$3.22 million	The Dinkey Creek Forest Restoration Collaborative reported \$3.22 million in total labor income from jobs supported and maintained by restoration efforts in 2019. From USFS (2019).
Grand Total	\$61.55 billion	

The total of all direct and indirect costs of wildfires throughout California in 2018 was estimated at \$148.5 billion. This estimate included destroyed and damaged properties, healthcare costs related to wildfire smoke exposure, and indirect losses from disruptions to regional and national supply chains (Wang et al. 2020). This paper estimates the total value of cobenefits of treatments in 2018 to be \$61.55 billion. While neither of these cost estimates can be realized in their entirety as treatments will not mitigate all of the assessed damage, it is helpful in comparing the potential costs and benefits of restoration treatments. As presented in section seven, this paper estimates roughly \$300 million a year is needed for treatments to attain overall forest resilience goals, this is just .48% of the value of the cobenefits or just 0.2% of the cost of total wildfire damages in 2018.

5.6 Intrinsic value

Above all else, the Sierra Nevada is a source of inspiration and a cherished cultural resource for Californians. Many of our state's crown jewels, including Lake Tahoe and Yosemite National Park, are in the Sierra Nevada. John Muir, a renowned conservationist penned that "after ten years spent in the heart of it, rejoicing and wondering, bathing in its glorious floods of light, seeing the sunbursts of morning among the icy peaks, the noonday radiance on the trees and rocks and snow, the flush of alpenglow, and a thousand dashing waterfalls with their marvelous abundance of irised spray, it still seems to me above all others the Range of Light," thus naming the Sierra Nevada the "Range of Light." For many Californians, including the indigenous people that first lived in the Sierra Nevada, there is no way to monetize its value, it is irreplaceable.

Climate change, bark beetles and wildfire threaten the continued existence of the Sierra Nevada as we know it today. Imagine Lake Tahoe with 70% less snow, the extinction of glaciers and snowfields in the high country and the conversion of millions of acres of mixed coniferous forests to chaparral scrubland and invasive grasses. Unfortunately, these changes are likely to become a reality without urgent and drastic action. Will we leave healthy forests for posterity to inherit and enjoy or only pictures and videos documenting distant memories of what once was? The decision is ours to make. Increasing treatments on the landscape today can create a sustainable Sierra Nevada in the future by mitigating catastrophic forest mortality from extreme wildfires, drought, and bark beetles.

VI: Barriers to implementing treatments at the landscape scale

Despite a growing consensus among academics, timber industry, conservation groups, environmental non-profits and government agencies that the scale and pace of thinning, prescribed burning, and reforestation treatments needs to be dramatically increased to protect the Sierra Nevada from catastrophic disturbances, a dire gap remains between the current pace and scale of treatments and what is needed. Currently, approximately 275,000 acres in across the State of California receive some sort of treatment each year. Precise estimates of the number of acres treated annually in the Sierra Nevada are not readily available. However, the USFS reported that in 2018 they treated 81,573 acres across six National Forests in the central and southern Sierra Nevada with another 96,632 acres in progress. Cal Fire's Vegetation Management Program treats an average of 25,000 acres per year and the USFS treats around 250,000 acres per year (USFS 2019a).

The Sierra Nevada Conservancy estimates that 6 million acres of forest in the Sierra Nevada are in dire need of treatment (Little Hoover Commission 2018). This is equivalent to about 40% of the roughly 15 million acres of Sierra Nevada forest. Other studies have estimated that less than 20% of the forested land in the Sierra Nevada needing treatment receives it (North et al. 2012). In comparison, the USFS set an internal goal of burning 500,000 acres a year on forest service lands throughout California (USFS 2021). A recent MOU between the State of California and USFS Pacific Southwest Region committed to treating a combined 1 million acres annually on forestland throughout California, but the MOU is non-binding. In fact, Cal Fire openly states that their 500,000 acres per year target in the MOU is not currently operationally feasible and should be treated as an aspirational goal (Forest Climate Action Team 2018).

There are many complex social, political, economic, regulatory, legal and practical implementation reasons that explain this gap, ranging from inadequate funding and financing to complaints about smoke from nearby communities. Based on a literature review and interviews with three practicing professionals involved with forest management in the Sierra Nevada, the greatest barriers to treatment implementation in the Sierra Nevada are a lack of public funding and private markets, regulatory burdens related to environmental permitting, low implementation capacity, practical implementation issues, and negative public perceptions of treatments. These barriers are discussed in greater detail below.

6.1 Economic barriers

Fuel reduction and reforestation treatments on public land are a classic public good. There is little private incentive to implement treatments, but society collectively benefits greatly as described in Section V. While treatments designed to protect high value assets in the wildland urban interface (WUI) can be paid for by the owners, these treatments are not implemented on the scale needed to have a discernable impact on carbon biogeochemical cycling. For example, many utilities and water districts have implemented treatments on land that they own or lease in the Sierra Nevada, but these treatments are designed to protect powerlines or water pumps and are limited to a few dozen or hundred acres around the assets' perimeter. Privately funded treatments will be pursued where profitable, not necessarily where they would be most beneficial to overall forest health. There is currently no private incentive to treat remote public lands, but it is possible that a private market for

such treatments could be created if treatments in Sierra Nevada forests could be certified as carbon credits that could be sold under California's AB 32 Cap and Trade regulatory framework.

Of the roughly 20 million acres in the Sierra Nevada bioregion, the USFS, Bureau of Land Management and National Park Service own about 60%. As federal budgets for treatments have stagnated, so has the number of acres treated. Additionally, the USFS uses a larger share of its overall budget for fighting extreme wildfires each year, often at the expense of thinning and prescribed burn treatments and forest restoration projects. In 1995, the Forest Service spent about 16% of its budget of fighting fires; in 2015 it was over 50% and is expected to grow to 67% by 2025. Similarly, during the same period there was a 39% decrease in USFS employees working in non-fire related positions (USFS 2015). This reduced capacity has stalled the pace and coverage of prescribed fire and thinning treatments on National Forest lands.

Thinning and prescribed fire treatment costs in the Sierra Nevada vary widely depending on several site specific circumstances including proximity to roads and site access, whether merchantable timber can be harvested to offset treatment costs, terrain and topography, timing, availability of fire crews and equipment and more. For example, sometimes new roads must be constructed and decommissioned to implement treatments, which is costly. In general, thinning projects are more labor intensive and expensive than prescribed fire treatments. Thinning treatments are generally more expensive than prescribed fire costs and managed wildfire costs are the lowest. Larger treatment areas have lower per acre treatment costs because economies of scale provide significant cost savings. Managed wildfire treatments, where low-severity fires are allowed to burn on remote federal lands while being closely monitored have the lowest costs and greatest opportunity for expansion (Miller et al. 2020). Legally, managed fire can only be used on federal lands as Cal Fire is required to put out fires and this strategy cannot be used in the WUI, which is constantly expanding.

Declining federal budgets for Sierra Nevada treatments have been partially offset by an increase in funding from the State of California and public-private partnerships. Good neighbor agreements allow state and local government landowners adjacent to USFS land to treat forest service land, usually with funding and oversight from the USFS. The 2018 farm bill first initiated the USFS' good neighbor authority. Tens of thousands of acres of USFS land in the Sierra Nevada was treated under good neighbor agreements in 2019. This year, Governor Gavin Newsome announced \$536 million in

additional funding for wildfire suppression, fire-resilient communities, and improvements in forest health. Such increases in public funding are encouraging, but still fall short of what is needed. It would conservatively take a billion dollars to meet the State’s goal of treating a million acres a year, assuming managed fire is not used. This assumes that it would cost on average \$1,000 to treat one acre, which is on the low side of the range of costs of treatments from the published literature. The \$1,000 an acre estimation assumes a combination of thinning, prescribed burning and managed wildfire treatments at the landscape scale and utilization of waste by products to offset costs. It is an optimistic estimation of treatment costs. Table 7 below shows the costs per acre of prescribed fire and thinning treatments in five different Sierra Nevada ecosystems. Site locations include Plumas National Forest in the Northern Sierra, the UC Blodgett research station in the Central Sierra, Sequoia National Park in the Southern Sierra and averages of Ponderosa and Lodgepole pine forests.

Table 7: Prescribed burning and thinning treatment costs per acre

Study Area	Prescribed Burn Cost per acre	Mechanical Treatment Cost per acre	Mechanical Treatment Revenue per acre	Mechanical Treatment net Cost per acre	Hand thinning + burning+ chipping Treatment Cost per acre
Central Sierra (Hartsough et al. 2008)	\$1,488	\$3,161	\$6,692	-\$3,530	NA
Southern Sierra (Hartsough et al. 2008)	\$1,254	NA	NA	NA	NA
Plumas County Fire Safe Council Oakland Camp Project (De Lasaux and Kocher 2009)	NA	NA	NA	NA	\$949
Sierra Ponderosa Forest (Rummer 2003)	NA	NA	NA	\$1,638	NA
Sierra Lodgepole Pine Forest (Rummer 2003)	NA	NA	NA	\$1,704	NA

Values were adjusted for inflation and are presented in 2021 dollars. Negative values indicate the treatment paid for itself and provided a return on investment.

Due to the high cost of landscape scale treatments on publicly owned land, many treatments have relied on the sale of merchantable timber within treatment areas to offset the cost of treatments.

Unfortunately, most of the material that is removed during understory thinning, overstory thinning, mastication and other mechanical thinning treatments is unmerchantable and becomes a waste byproduct. Few markets currently exist for this waste material, although the woody debris can sometimes be burned to generate bioenergy. The cost to transport this moist, low-energy material to the nearest bioenergy facility is often prohibitive; there are only 12 biomass energy facilities currently in operation adjacent to the Sierra Nevada (UC ANR 2020). Leaving the waste onsite in burn piles is often the end result of these market constraints. Leaving the waste byproducts onsite decreases the efficacy and net carbon benefit of the treatment. New forestry products such as biochar, laminated wood products and wood cellulosic nanotechnology show promise in increasing the utilization of treatment waste products and offsetting treatment costs. Additional research into utilization pathways for this waste material could help create a private market that would help defray the costs of treatments, leading to more widescale adoption. In addition to additional research, zero interest loans and other subsidies for companies that manage treatment byproducts would help drive the adoption of new and innovative uses for these waste byproducts.

6.2 Environmental regulations and legal issues

The approval and funding process for implementing thinning or prescribed burn treatments varies depending on land ownership and who is conducting the treatment. A mix of private, state government and federal funding and jurisdictions can further complicate treatment implementation (Miller et al. 2020). This often results in fragmented treatment, which reduces efficacy as wildfires transcend administrative boundaries. Figure 15 below explains these implementation pathways.

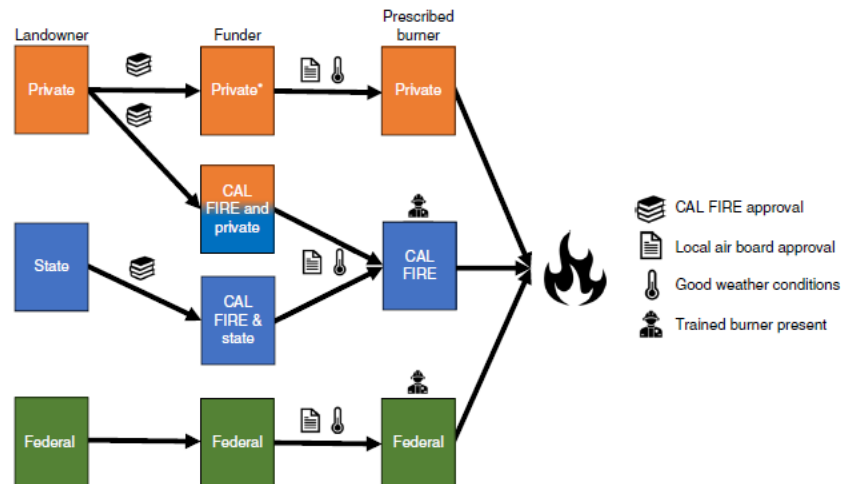


Figure 15: The various approval processes for treatments on federal, state and private land in California. From Miller et al. (2020)

Projects that are carried out on state or federal land or use state or federal funding trigger California Environmental Quality Act (CEQA) or National Environmental Policy Act (NEPA) reviews. These permitting processes can be onerous, litigious, costly, and fraught with controversy. Completing the CEQA/NEPA process for a landscape scale treatment can take between 2-6 years in the Sierra Nevada (J. Moghaddas, Spatial Informatics Group, pers. comm.). Environmental interest groups may sue land management agencies to complete a full Environmental Impact Statement instead of an Environmental Assessment or a Categorical Exclusion. Completing an EIS requires a team of environmental professionals including biologists, hydrologists, fire ecologists, risk assessors and other personnel. Such effort can divert resources intended for treatments towards environmental planning. Sometimes, a planned treatment may get delayed due to funding, crew availability or weather constraints and the EPA/CEQA approval expires before the treatment can be implemented and the NEPA/CEQA process must start all over again. Conversely, the agreements in place to complete a treatment may also expire before NEPA/CEQA approval is granted (J. Moghaddas, Spatial Informatics Group, pers. comm.). Because many treatments are reapplied in the same area over 5 to 10 years, the need to complete multiple NEPA/CEQA reviews can prevent a treatment project from moving forward.

The Endangered Species Act can also limit treatment location, size and burn severity for all treatment projects. Dense, overgrown forests are a priority area for treatment applications, but also often harbor special status species and their protected activity centers (e.g., nests or dens). Impacts to the Pacific

Fisher and the Northern Spotted Owl are two of the most common reasons environmental groups have sued under the ESA to stop treatments (Collins et al. 2010).

Additionally, prescribed burning treatments in California must be approved by the local air board or air quality management district. Air districts limit burn days to days when atmospheric conditions are favorable to smoke dispersion. Many have criticized this approach pointing out that the PM_{2.5} emissions from wildfires are not regulated and are much more significant than emissions from prescribed burns. However, because the ignition source is human caused, prescribed fires are subject to regulation under the Clean Air Act.

Liability concerns over escaped fires from prescribed burns also discourage all landowners from burning. SB 1260 helped address this by releasing private landowners of liability for escaped burns if they complete an approved training course and follow implementation guidelines set by Cal Fire (Miller et al. 2020). Designated “burn bosses” can still be held liable for escaped fires and face severe career repercussions even if they are not found to be personally liable. On the flip side, burn bosses and Fire Management Officers face no potential repercussions for deciding not to burn. As a result, some fire professionals have reported being overly risk averse to the point that prescribed burns with minimal risks are still not implemented. A change in liability laws for state and federal fire officials similar to SB 1260 would help change the culture around prescribed burning.

6.3 Practical Implementation issues and negative public perception

Sometimes, prescribed burning or thinning treatments are simply not operationally feasible. Prescribed burns close to populated areas in the WUI require careful management and in some areas, the WUI has become too dense to safely light a prescribed burn. As the WUI continues to encroach into National Forest land, even more land will become untreatable with prescribed fire. Many treatment areas are also inaccessible for mechanical treatment because they are in roadless, steep and rough terrain. Although it may be possible to construct a road in these areas, the cost of building and maintaining the road is prohibitive. Managed and prescribed fire are viable treatment alternatives in these areas. However, mechanical treatments are often a prerequisite for prescribed fire because forests are so overgrown that a prescribed fire cannot be safely lit before some thinning has occurred. These constraints result in fragmented treatment areas, which increases the cost of treatment per acre and

reduces the efficacy of the treatment. Of the 10.7 million acres of Sierra Nevada land owned by the USFS, only 25% is estimated to be available for mechanical treatment due to current legal, operational, and administrative constraints (North et al. 2015).

A survey of 70 federal and state government agency, tribal and NGO fire managers identified a narrow burn window as the most significant impediment to prescribed burn treatments in Northern California (Quinn-Davidson and Varner 2012). Burn windows are limited by numerous variables including fuel moisture conditions, protected species presence, availability of crews and equipment, air quality district approval and atmospheric conditions. As climate change worsens and snow in the Sierra Nevada melts quicker the “shoulder season”, usually between April and mid-May has fewer days where fuel moisture conditions are safe to burn (R. Marshall, USFS, pers. Comm.) Increasing temperatures also increases the formation of Ozone, which in turn further restricts the number of days air districts are willing to approve prescribed burns.

Attitudes towards thinning and prescribed burning treatments are slowly changing, but negative perceptions persist. While complaints from neighboring communities about smoke impacts from burning treatments cannot unilaterally stop a treatment project, they do make it more difficult for permitting authorities such as the local air district as well as government agencies conducting the burns. Some environmental interest groups remain skeptical of treatments because they fear they might be improperly used to circumvent environmental protections and restrictions on logging. Lawsuits from these groups have slowed or stopped several Sierra Nevada treatment projects. However, there is a growing consensus that treatments are urgently needed, and lawsuits are not as common as they were 20 years ago. Prior to 1972, there was only one journal article written on prescribed fire as a forest management tool. Today, there have been over 4,000 written (Kolden 2019). Public opinion ultimately shapes public policy and increased public support of treatments has already led to legislative reforms in California aimed at making it easier to conduct treatments, such as SB 1260. Additional legislative remedies and environmental management recommendations to increase the pace and scale of treatments are presented in Section VII.

6.4 Lack of implementation capacity

Treatment implementation requires a robust workforce of highly skilled forestry and firefighting professionals, specialized equipment such as masticators, knuckle boom loaders and fire engines and

large, dedicated, infrastructure (e.g., sawmills). There is currently a lack of all these inputs, leading to many treatments not proceeding from the planning to implementation stage. State and federal firefighting agencies do not have crews dedicated to implementing treatments. As a result, fire crews are often unavailable to complete burns as they are called to fight wildfires in other parts of the state or country (Miller et al. 2020). Specialized equipment and trained operators are also in short supply and contribute to high treatment costs.

Even when public funding for thinning and prescribed burn treatments is dramatically increased, contractors may still be unavailable or unwilling to bid on the contracts. The capital costs, barriers to entry and risks for small businesses are high and the industry returns are low. A single masticator can cost over \$500,000 and at least \$3-4 million is likely needed to start a small logging business capable of carrying out mechanical thinning operations (J. Moghaddas, Spatial Informatics Group, pers. Comm). One of the largest contracts in the Forest Service's history was the Four Forest Restoration Initiative, which aimed to treat 2.4 million acres across four national forests in Arizona. Initially issued in 2009, the contract has been significantly delayed and has treated only 30% of the intended acres because contractors could not figure out how to economically remove thinned biomass from the forest (Quinton 2018). Portions of the project where a sawmill and bioenergy facility exist have been much more successful. The contract was modified this year to extend the period of performance from 10 to 20 years to reduce market uncertainty and guarantee a source of income to stimulate an innovative private market for the waste material (Quinton 2018).

Significant infrastructure with high capital costs such as mills, storage facilities and wood distribution networks are needed to capitalize on small diameter timber, wood chips, mulch and other products generated from thinning treatments. Oftentimes, these facilities have to be modified to accept the small diameter timber from thinning treatments. There are few sawmills left in California, with only one mill serving the entire Southern Sierra Nevada. That mill's capacity was easily exceeded by the high tree mortality in Sierra National Forest in 2015 and after the Creek Fire in Fresno and Madera counties in 2020 (Daniel 2015). California's forest products industry's annual capacity to process sawtimber has decreased by nearly 70 percent, from 6 billion board feet in the late 1980s to 1.7 billion board feet in 2009. As of 2006 there were just 33 sawmills, 25 bioenergy plants, 10 bark and mulch plants, 4 reconstituted board plants, and 3 manufacturers of other primary wood products in the state of California (Morgan et al. 2006). With such limited capacity from the forest products industry, it is

difficult to quickly expand mechanical treatment to the landscape scale because merchantable timber cannot be economically utilized to offset treatment costs.

VII: Environmental management recommendations

The current condition of Sierra Nevada forests has been shaped by over a century of wildfire suppression and two hundred years of anthropogenic driven climate change. Undoing this legacy will take a sustained commitment lasting decades and cost billions of dollars. A robust body of literature has documented that thinning, prescribed fire and restoration treatments are an effective way to build overall forest resilience to wildfire, drought, and bark beetles. This increased resilience will help maintain the Sierra Nevada as a stable carbon sink over the long-term. To increase the pace and scale of treatments to the levels needed to tackle these pressing threats a dramatic increase in public funding, development of a trained workforce, adjustment in environmental regulations, and cultivation of robust private markets in the forest products industry to support treatment work is needed.

Thankfully, the three most significant barriers to implementing treatments identified in section VI, economic barriers, environmental laws and regulations, and limited implementation capacity are all within societal control. We can increase funding, adjust environmental regulations, and invest in developing the required workforce and equipment to complete the work. Implementing the environmental management recommendations outlined below will protect Sierra Nevada forests by increasing their resilience and carbon stability over the long-term.

7.1 How many acres in the Sierra Nevada do we need to treat and where?

Treating 300,000 acres per year in the Sierra Nevada is adequate to meet the desired management outcome of improving the overall stability of carbon stocks in the Sierra Nevada bioregion. The Sierra Nevada bioregion is approximately 20 million acres, 15 million of which are forested (USGS 2021). A goal of treating 40% of this area over the next twenty years as recommended by the Sierra Nevada Conservancy yields an average of 300,000 acres per year (Little Hoover Commission 2018). Assuming an ambitious cost of \$1,000 per acre treated, \$300 million in federal funding would be needed each year to meet treatment goals in the Sierra Nevada. In comparison, Cal Fire spent over \$1 billion on suppression costs alone in 2020 and there was over \$14 billion in combined suppression and property loss costs in 2017 throughout California (Barrett 2018). While Governor Newsome's \$536 million commitment toward wildfire prevention is greater than the \$300 million needed, most of the funds are focused on

suppression efforts such as hiring additional firefighters, equipment and human resilience such as home hardening, education and better evacuation systems, not preventive forest management treatments.

A goal of 300,000 acres per year does not account for the need to retreat areas. The frequency of needed retreatments varies depending on the type of treatment, type of forest, changing climatic conditions, post-treatment land use and other variables. However, in general retreatments in mixed conifer forests in the Sierra Nevada are needed every 8-15 years (Chiono et al. 2012). Others have estimated this number to be 8-10 years (Vaillant and Dailey 2013). This means that treating 300,000 acres per year is an underestimate of the number of acres that should be treated. Currently, the number of acres treated with prescribed burns throughout all of California is about 45,000 acres per year (Miller et al. 2020). To reach the goal of treating 300,000 acres per year in the Sierra Nevada, areas burned by low-severity wildfires should be counted towards the goal. Greater utilization of managed wildfire presents a valuable opportunity to expand treatments without spending billions of dollars.

Treatments should be prioritized in areas that are the most likely to burn and overlap with WUI assets. Foster et al. (2020) and other studies emphasize the importance of treating areas that are likely to experience a wildfire to maximize the return on investment for carbon emissions. If an area is treated but does not experience a wildfire within 8-10 years (effective period for most treatments), then the emissions generated by the treatment are not offset by future emission reductions. Because the probability of a given area being burned by a wildfire is relatively low (<2%), treatment areas need to be large to intersect with wildfires and should be prioritized in areas with high ignition potential (Foster et al. 2020). Areas of high ignition potential include campgrounds, canyons, steep valleys, and high voltage powerline utility easements. There are 2,743,634 acres available for treatment within the WUI according to Cal Fire, these areas should be overlaid with wildfire risk maps to prioritize treatment locations (Forest Climate Action Team 2018).

7.2 Create and fund a federal Climate Conservation Corps to implement treatments

With millions of Americans still out of work due to the COVID-19 pandemic, a federal Climate Conservation Corps modeled after the original Civilian Conservation Corps from the 1930s New Deal era could put Americans, especially those from underserved communities, back to work restoring our forests. The original “CCC boys” of the 1930’s left behind a legacy that endures to this day. Countless public works projects around the country- from libraries in San Francisco to trails and campgrounds in Yosemite National Park are still thoroughly enjoyed by the public. The passage of the \$1.9 trillion 2021

COVID-19 Stimulus Package demonstrated a newfound willingness to reverse decades of neoliberal economic hegemony and instead make substantial public investments at the local, state, and federal levels. Now, an equally large infrastructure bill, the American Jobs Plan, is being debated in Congress and funding for building resilience to extreme wildfires has been identified in President Biden's proposal. This infrastructure bill should allocate billions towards expanding treatments on the landscape in the Sierra Nevada through a publicly funded Climate Conservation Corps program. While carrying out restoration and conservation projects in forests would be the primary focus of the CCC in California, other regions could focus on different priorities.

The CCC would provide decent paying jobs to members of rural underserved communities adjacent to Sierra Nevada National Forest lands as well as other underserved communities throughout California. Residential camps already in existence such as the Minarets Work Center in Sierra National Forest could be put back into service to house corps members from other parts of the state. Pay and benefits must be high enough to attract a workforce and provide a living wage.

California already operates two similar programs that have been proven to be highly effective in meeting these goals: the California Conservation Corps and the California Conservation Camp. These programs were discussed in section 6.4 and employ about 7,300 members throughout the state. A federal program is needed to augment these existing state programs to treat more acres and to maintain a cache of the necessary equipment and trained professionals to implement treatments. Seventy-five percent of the CCC crews could be dedicated solely to undertaking treatments to avoid resources intended for preventive treatments being diverted to wildland firefighting.

This approach would reverse ongoing trends of privatization in firefighting where services are routinely contracted out. Cal Fire and the USFS have had difficulty attracting competitive bids for fuel reduction projects because they are not very profitable. The government needs to address this classic public goods problem by developing the workforce and maintaining the equipment needed to implement treatments, even if it is not profitable for the private sector to do so.

7.3 Streamline environmental regulations

While the California Environmental Quality Act (CEQA) and National Environmental Policy Act of 1969 (NEPA) provide many public benefits, such as the opportunity for public comment on proposed plans, they are also a barrier to expanding treatments. It is worth noting that Miller et al. (2020) interviewed 45 federal and state government employees, non-profit representatives, academics, and legislative staff

and none of them proposed eliminating or reducing the environmental protections afforded by NEPA and CEQA despite identifying it as a significant barrier. Streamlining the NEPA process to approve categorical exclusions for all treatments within a specified buffer of the WUI is one way to reduce regulatory burdens for projects that are urgently needed to protect life and property (J. Moghaddas, Spatial Informatics Group, pers. comm.). Completing one programmatic EIS for multiple treatments within an entire forest could also help reduce CEQA and NEPA regulatory barriers. Additionally, extending the period for which a NEPA or CEQA analysis is valid would give treatment personnel more flexibility in implementing treatments when unforeseen circumstances such as wildfires, COVID-19, and atmospheric conditions result in delays.

The number of autumn days with extreme wildfire conditions in the Sierra Nevada has more than doubled since the 1980s (Goss et al. 2019). We cannot afford 2-6 years for CEQA/NEPA analyses to complete the treatment planning process. The consequences of failure to act, complete destruction of habitat with little chance for long-term restoration, is undoubtedly worse than a less rigorous EIS. Reframing conversations on expanding treatments around the cost of failure to negotiate may help convince reticent stakeholders to support greater uses of categorical exclusions and environmental assessments to reduce the regulatory burden of NEPA (Wood and Jones 2019).

Currently, a patchwork of rules and regulations from local air quality management districts dictate when prescribed burns can occur. The U.S. EPA issued *Exceptional Events Guidance: Prescribed Fire on Wildland that May Influence Ozone and Particulate Matter Concentrations* in 2018 to aid air districts in evaluating when prescribed burns may qualify for an exceptional event exemption under the Clean Air Act. Further clarification from EPA on how emissions from prescribed burns are regulated under the Clean Air Act would be helpful and more flexibility is needed. Adverse respiratory and cardiovascular health impacts from smoke are the same regardless of whether the smoke comes from a wildfire or prescribed burn. Regulations should reflect this reality. In the long run, emissions from prescribed burns will be lower than emissions from wildfires with fewer adverse health impacts. Further revising Clean Air Act guidance to encourage prescribed burns would help expand the burn window and eliminate a significant barrier to expanding treatments.

Standardization of burn rules across air boards, particularly for projects crossing multiple jurisdictions, would help streamline the application process for burn managers. Additionally, state-wide adoption of

California's Prescribed Fire Information Reporting System could improve recordkeeping on the number of acres treated by prescribed burns each year.

7.4 Expand treatments by building on existing programs

The majority of Sierra Nevada forestland is managed by the USFS. The USFS Collaborative Forest Landscape Restoration Program (CFLRP) was created in 2009 by the Forest Landscape Restoration Act to promote biologically, economically, and socially sustainable forest landscapes through a collaborative partnership between public and private partners. Restoration of natural fire regimes is a cornerstone of the program, which receives around \$40 million in federal funding each year. Nationally, the program has treated 3.8 million acres throughout the U.S. with prescribed burns and mechanical thinning since its inception.

Two CFLRP projects have taken place in the Sierra Nevada: The Dinkey Creek Collaborative in Sierra National Forest and the Amador-Calaveras Consensus Group in El Dorado and Stanislaus National Forests. The Dinkey Creek Collaborative has successfully treated nearly 36,000 acres since its inception in 2009 through 2019 (USFS 2019b). In 2019, the Dinkey Creek Collaborative supported 69 jobs in fields ranging from logging to watershed restoration and received roughly \$460,000 in CFLRP funds. The sustained funding (10+years) and requirements to coordinate with state, local and private partners make the CFLRP unique. These characteristics allow grant recipients to leverage the program to attract additional funding for restoration projects from external sources. Greenhouse Gas Reduction Funds from the State of California, Cal Fire funds and funds from private entities such as Southern California Edison have been used by the collaborative to plant new saplings in fire damaged areas, restore high montane meadows and conduct treatments near important hydroelectric infrastructure (USFS 2019). The CFLRP has a proven track record of successfully implementing millions of acres of treatments on National Forest lands and is worthy of funding for additional projects in the Sierra Nevada.

The Cal Fire Vegetation Management Program (VMP) currently treats about 25,000 acres per year and aims to treat 60,000 acres per year by 2030. The VMP Cal Fire allows private landowners to contract with Cal Fire to complete prescribed burns and some types of mechanical treatments on their land. Cal Fire assumes all liability for escaped fires and uses local Cal Fire crews to complete the work. Cal Fire is responsible for completing treatments on land owned by the state government (2.2% of California's forests) and private landowners (39%) (Miller et al. 2020). Cal Fire's current goal is not adequate to

ensure long-term carbon stability in the Sierra Nevada. Additional state funding for Cal Fire crews dedicated to the VMP could help further increase the number of acres treated each year.

7.5 Develop private markets to support waste product utilization and increase treatment implementation capacity

While additional federal funding for treatments is greatly needed, it is more likely to be a sustainable source of long-term financing if treatment costs can be reduced. Increasing the utilization of treatment waste byproducts such as slash, woodchips, and small diameter timber remains a significant barrier to lowering treatment costs. Developing private markets for these byproducts should be subsidized by research and development grants to universities to find innovative uses for these materials. Since 2004 the USFS has spent \$36.4 million on grants in California to help diversify wood and biomass markets (USFS 2019).

Higher utilization of waste byproducts also has significant implications for ghg emissions. Burning biomass for energy generation purposes using a fluidized boiler emits 98% less PM, CO and CH₄ and 14% less CO₂ than open pile burning in the forest (Forest Climate Action Team 2018). Substituting wood products for conventional building materials such as bricks displaces an average of 3.9 tons CO₂e per ton of drywood used. Approximately 61 percent of wood product carbon returns to the atmosphere after 100 years, leading to annual sequestration of 0.337 MMT CO₂e in harvested wood products per year in California (Forest Climate Action Team 2018).

Additionally, private markets for support services needed for treatments such as heavy equipment operators, loggers, sawmills, and forest product industries should be supported where possible. Small business can be supported with low to no interest loans to purchase capital equipment, multi-year contracts with public agencies to provide consistent revenue and making sure contractors get paid within two weeks of when services are rendered. Dramatic increases in public funding will eventually be exhausted if there is no private market for support services public agencies need for implementing treatments. Subsidized equipment cooperatives where several companies could share equipment could help lower barriers to entry for small business owners operating logging, trucking, and forest product processing equipment. Government assistance to develop these private markets may help reduce treatment costs for the government in the long-term as public agencies responsible for treatments would not have to maintain all the equipment and human capital needed to implement treatments if a viable private market exists.

7.6 Other recommendations

As the USFS shifts towards a more collaborative model of forest management on National Forest Lands, partnerships with individual small landowners can help implement treatments in the few areas where a private incentive for treatment exists- adjacent to homes, businesses, schools and private property. Currently, good neighbor agreements can only be used by public agencies and funding is still limited by federal funding. A different type of good neighbor agreement for private landowners adjacent to National Forest lands who have a vested interest in protecting their own property is needed. Property owners should be able to petition the USFS to do the work according to specifications and requirements to be determined by the USFS. If the USFS is unable to treat the land within one-year, private property owners would be allowed to treat the land using a private contractor or on their own. The agreement would provide liability protection for landowners. Good neighbor agreements can simplify the different approval processes for completing treatments within different jurisdictions, leading to more comprehensive and effective treatments.

Central to verifying the efficacy of treatments is the underlying data on which carbon stock and flux estimates are based. Strengthening the USFS Forest Inventory Analysis Program by increasing the number of monitored plots and sampling frequency would aid our understanding of carbon biogeochemical cycling in the Sierra Nevada. Because many plots are only measured once every 10 years, it is difficult to use this data to measure carbon fluxes resulting from a single disturbance, such as a wildfire or drought.

Perhaps the greatest barrier to increasing the pace and scale of treatments is a lack of political will and social awareness to address the issue. Inaction and failure to gain consensus amongst stakeholders should be framed in terms of the cost of failure. The Sierra Nevada is at an ecological tipping point, with large scale conversion of mixed-conifer forest to chaparral scrubland likely in the upcoming decades. Emphasizing the permanent loss of these treasured ecosystems by providing renderings of what iconic landscapes such as Tahoe and Yosemite will look like if we continue business as usual will help motivate the urgency that is desperately needed to accelerate treatments despite disagreements about certain policy specifics. In short, stakeholders must be reminded that the no action alternative is often a far worse outcome than not achieving their desired policy goal.

VIII. Conclusion

The Sierra Nevada stores a tremendous amount of carbon in its aboveground and belowground pools, although estimates vary widely from a low estimate of 3,119 MMT CO₂e for all aboveground biomass in California to a high estimate of 3,500 MMT CO₂e for aboveground and belowground carbon in the Sierra Nevada. However, the range of estimates demonstrates that the carbon sink is substantial and can significantly increase California's total greenhouse gas emissions if released into the atmosphere. Determining whether the Sierra Nevada is a net carbon sink or source in a given year is not critical to managing carbon in the Sierra Nevada. Ensuring that the majority of carbon already stored in the Sierra Nevada remains stable over the long-term should be the paramount goal of carbon management in the Sierra Nevada.

Sierra Nevada forests are facing an unprecedented crisis driven by climate change and a century of fire exclusion. Dense, overgrown forests are more susceptible to major disturbance such as wildfires, drought, and bark beetles. These disturbances have exponentially increased in the last ten years and have driven extraordinary mortality, ravaging millions of acres of Sierra Nevada forests. Additionally, the disturbances are often severe enough to prevent normal forest regeneration, resulting in an alarming conversion of coniferous forests to chaparral scrubland and grassland.

A wealth of literature provides strong evidence that thinning, prescribed fire and reforestation treatments increase overall forest resilience to wildfire, drought and bark beetles. Multiple lines of evidence including direct measurement studies, modeled simulations and long-term studies from dozens of research plots have demonstrated the efficacy of treatments in reducing wildfire severity and spread, and drought and bark beetle related mortality. However, an alarming gap exists between the number of acres in need of treatment (over 15 million statewide) and the number of acres currently treated annually (around 275,000). To maintain the Sierra Nevada as a net carbon sink over the long-term this paper estimates around 300,000 acres would need to be treated each year, conservatively costing about \$300 million annually. The most significant barriers responsible for the dearth of treatments are economic barriers, environmental regulations, and low implementation capacity. To address these barriers, the federal government should fund and create a Climate Conservation Corps modeled after the original Civilian Conservation Corps of the 1930's to directly implement treatments.

NEPA and CEQA review process should be modified by to facilitate analyses of entire fireheds instead of individual analyses for each prescribed burn. Research into innovative uses for waste byproducts can help reduce treatment costs and expand treatments.

The benefits to long-term carbon stability alone are significant enough to warrant public investment, especially in light of considerable cobenefits such as protection of life and property, improved air quality, increased water quality and quantity, and economic opportunities for rural and underserved communities. However, when the cobenefits are accounted for, thinning, prescribed fire and reforestation treatments yield substantial returns beyond the initial investment. In 2018, the cobenefits of treatments were estimated to be valued at \$61.55 billion, which is only .48% of the expected cost of implementing the treatments.

If we do not act now to increase the pace and scale of treatments on the landscape, we risk further exacerbating the climate crisis. More homes and lives will be lost to wildfire. Apocalyptic smoke blotching out the sun will become a regular occurrence each summer. Large parts of the Sierra Nevada will be irreparably converted from coniferous forests to chaparral scrubland and grassland and treasured landscapes such as Yosemite National Park and Lake Tahoe will be degraded. The Sierra Nevada as we know it will shift to a completely different ecosystem, supporting different plant and animal life. California could reduce its ghg emissions from all electricity generation by 82% overnight and the net benefit would be cancelled out by tree mortality in one year in the Southern Sierra Nevada. To meet its ghg reduction goals, California must ensure the long-term viability and stability of carbon stocks in the Sierra Nevada by increasing the pace and scale of thinning, prescribed fire and reforestation treatments.

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